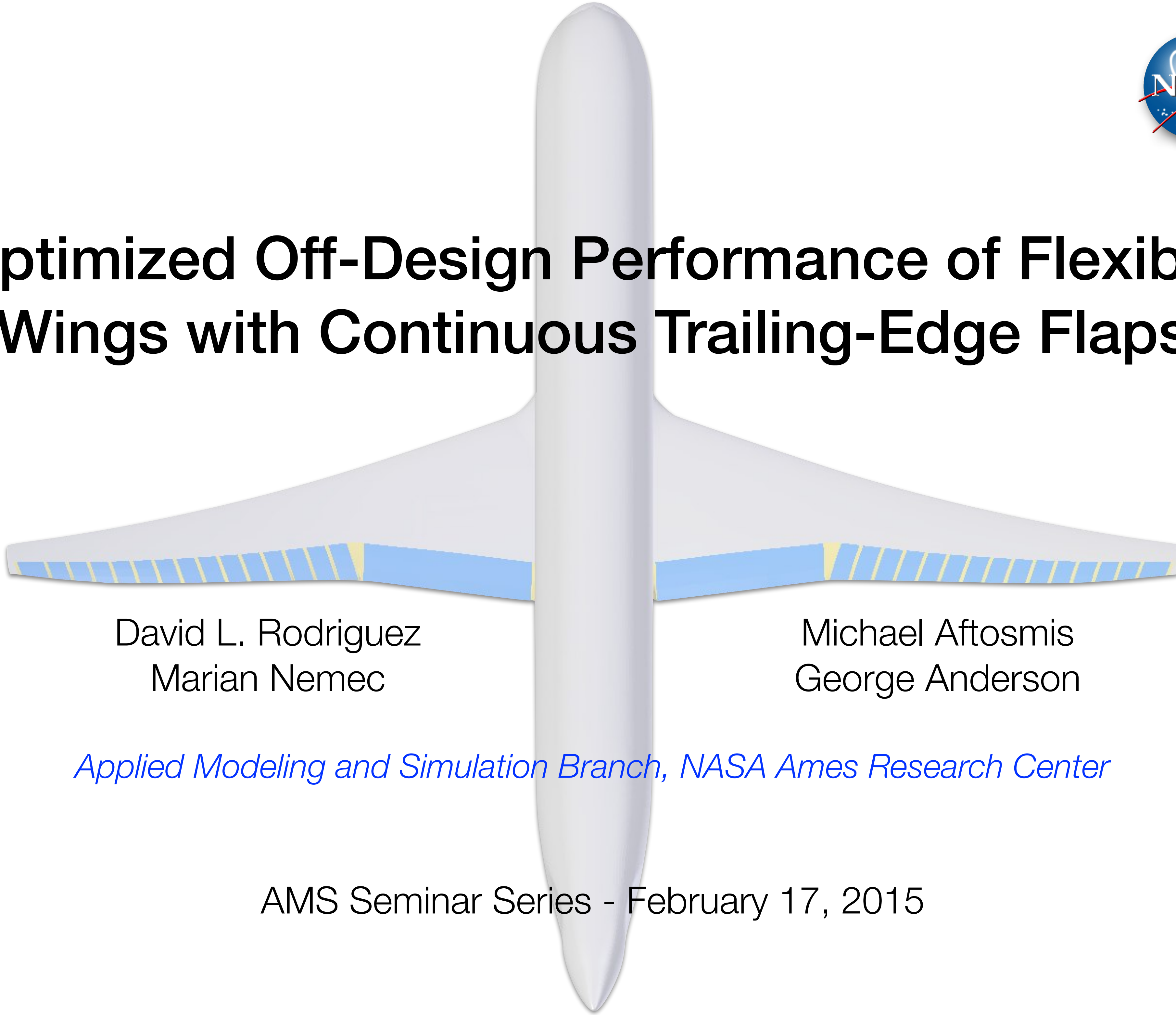
Optimized Off-Design Performance of Flexible Wings with Continuous Trailing-Edge Flaps



David L. Rodriguez
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Applied Modeling and Simulation Branch, NASA Ames Research Center

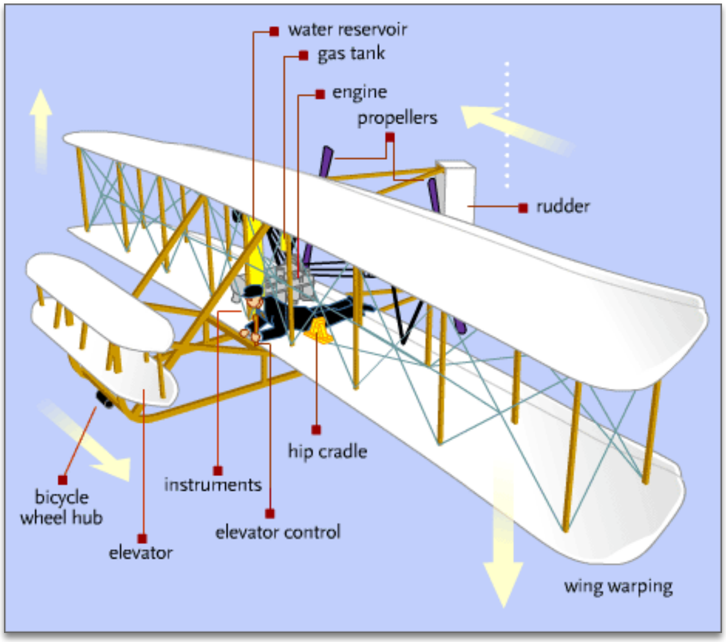
AMS Seminar Series - February 17, 2015

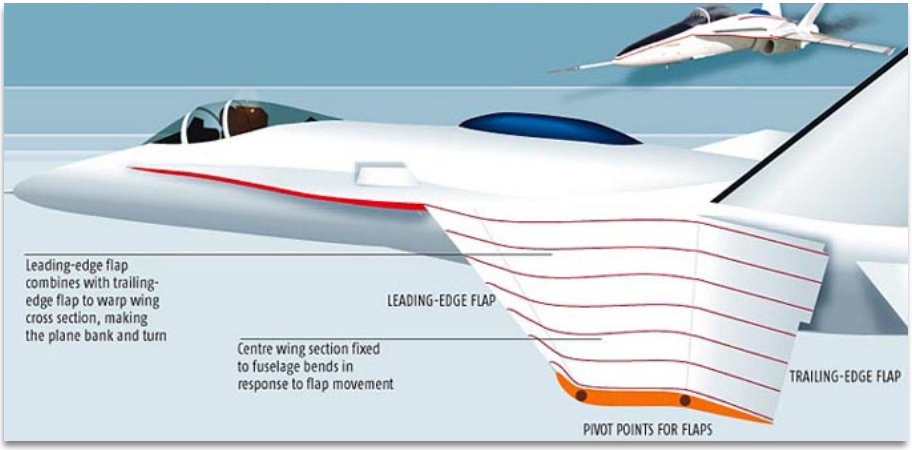
Modern Wing Structures Technology

- Many new concepts have high aspect ratio, light, very-flexible, composite wings
- Wing shape varies greatly throughout mission profile
- Boeing 787 wing tips deflect 10 feet at cruise!

Wing Morphing Technology

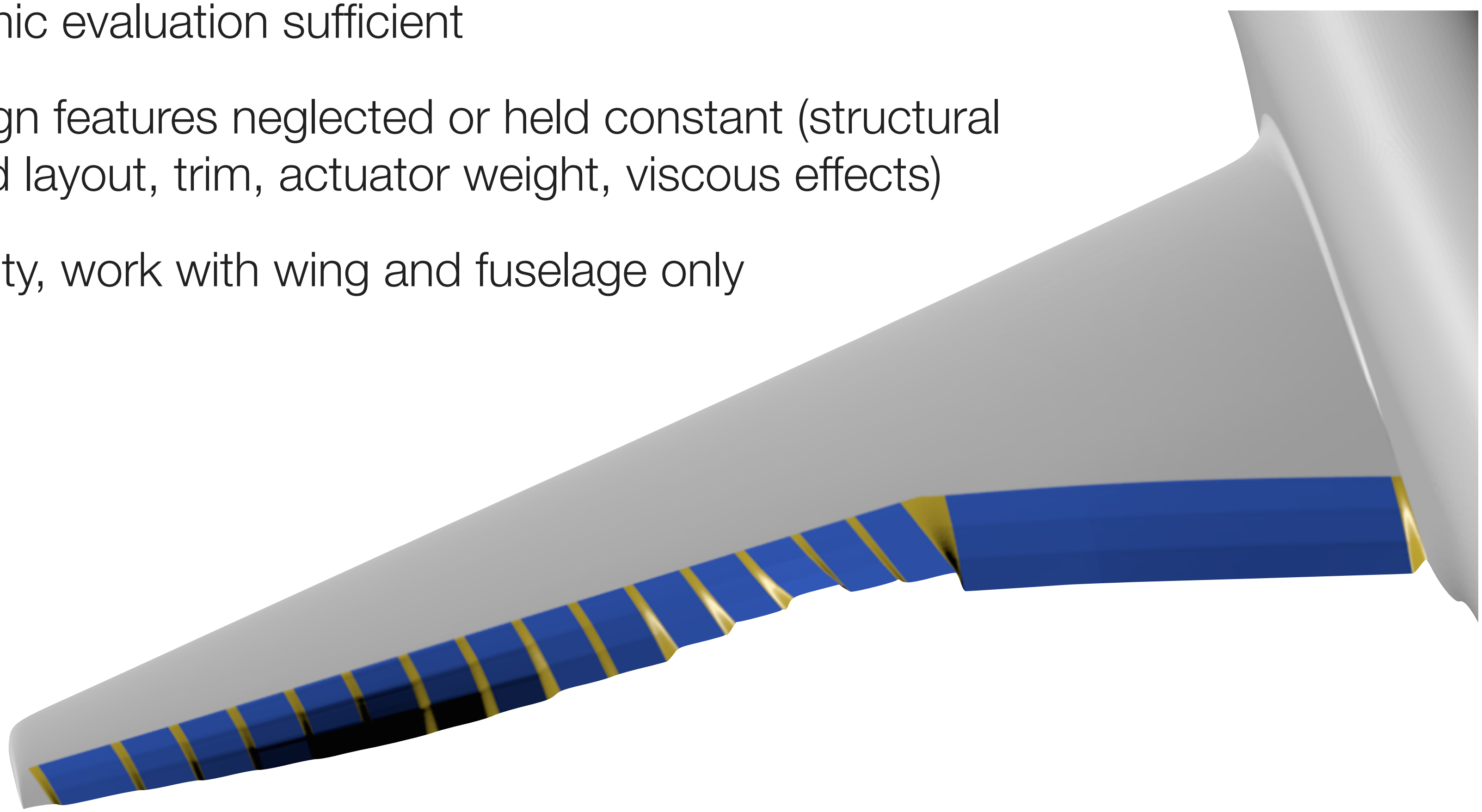
- Wing morphing has been used since the beginning of human flight
- Basic concept is to actively reshape the wing in flight to improve performance and/or control
- One concept currently being researched is the VCCTEF





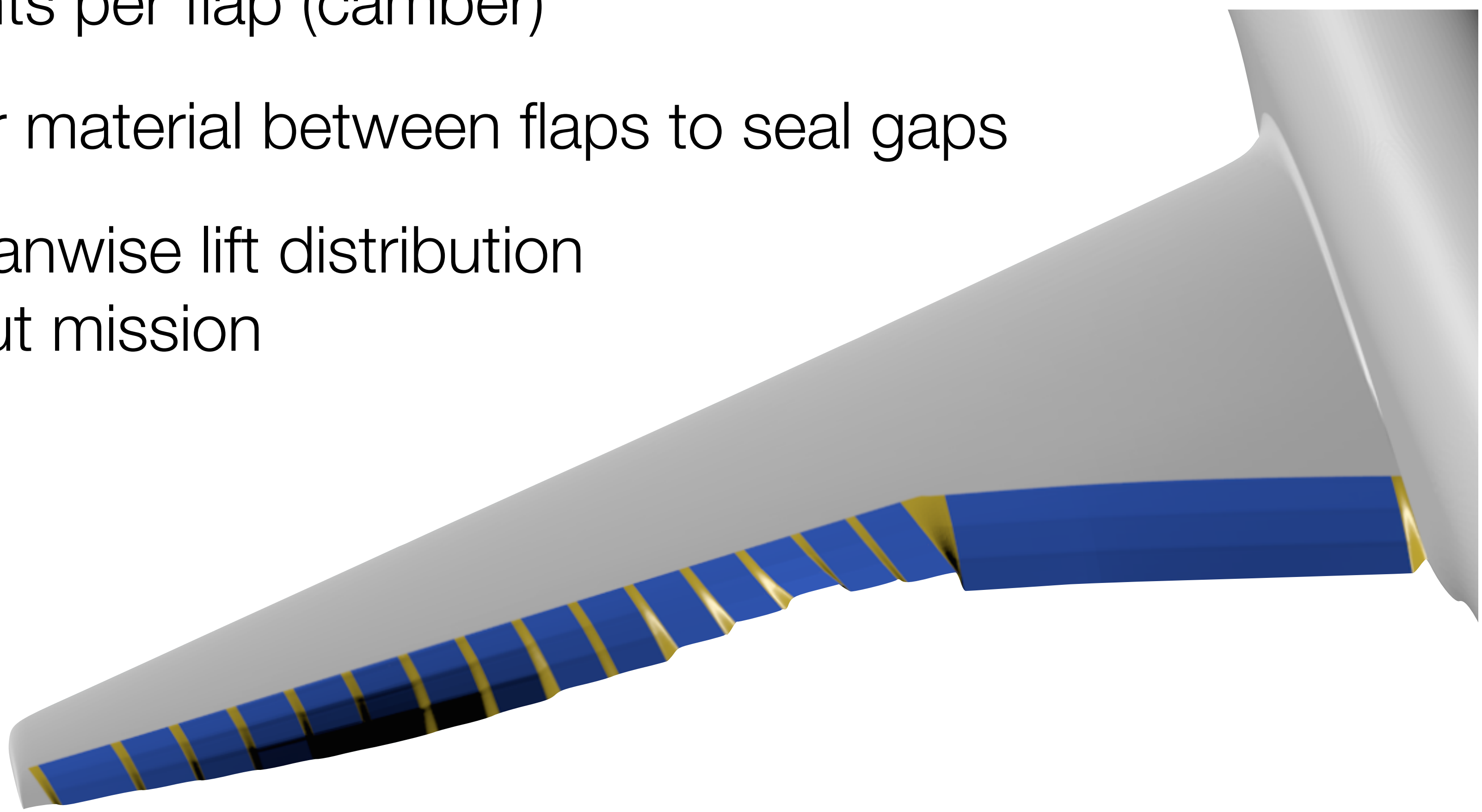
Goal: Evaluate VCCTEF Concept

- **V**ariable **C**amber **C**ontinuous **T**railing **E**dge **F**laps
- Evaluate the maximum potential benefit of VCCTEF on a generic transport model (GTM) aircraft at cruise
  - aerodynamic evaluation sufficient
  - other design features neglected or held constant (structural weight and layout, trim, actuator weight, viscous effects)
  - for simplicity, work with wing and fuselage only

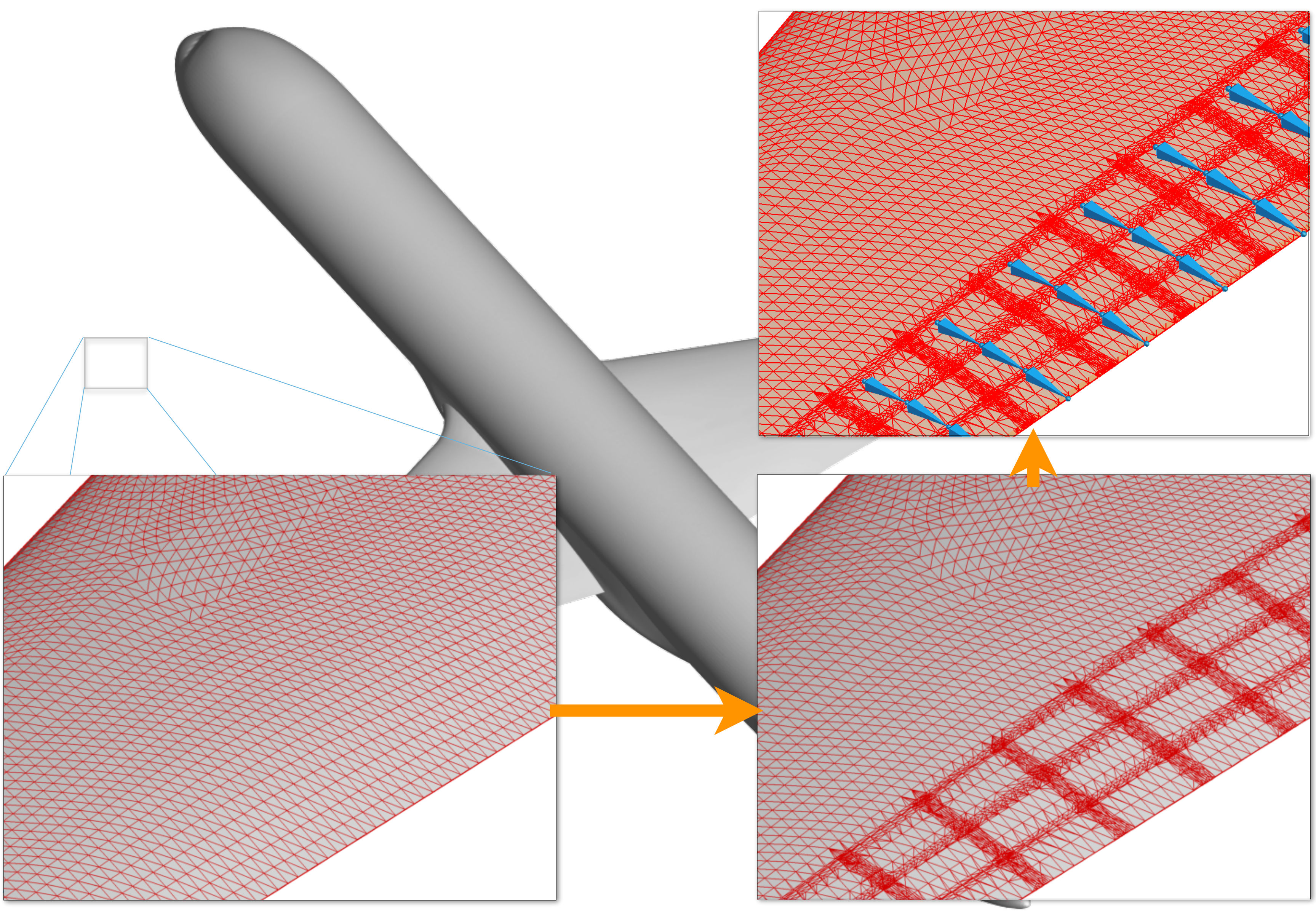


VCCTEF Layout on GTM

- Flaps over most of the span of the wing
- 1 large inboard flap, 14 smaller outboard flaps, 1 aileron
- 3 segments per flap (camber)
- Elastomer material between flaps to seal gaps
- Tailors spanwise lift distribution throughout mission

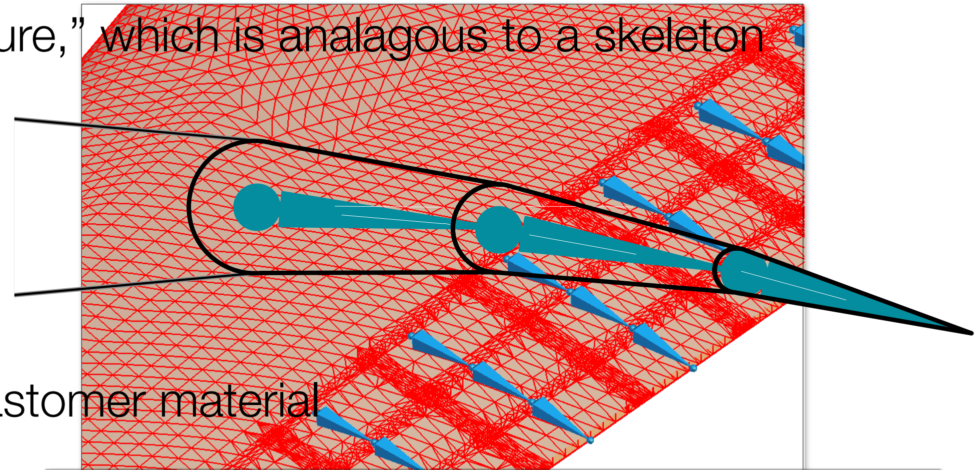


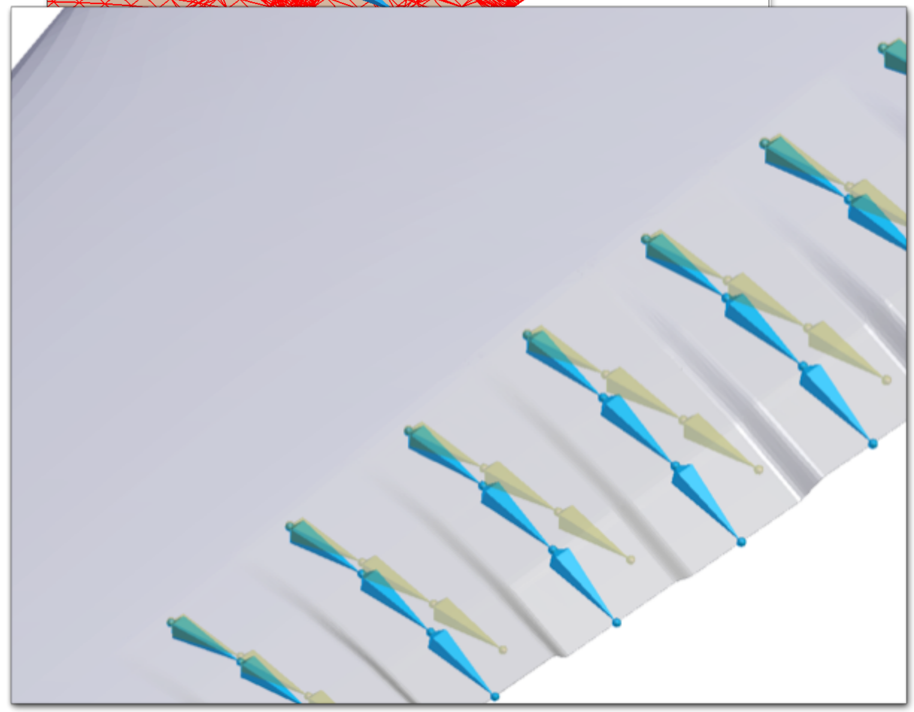
Modeling the VCCTEF



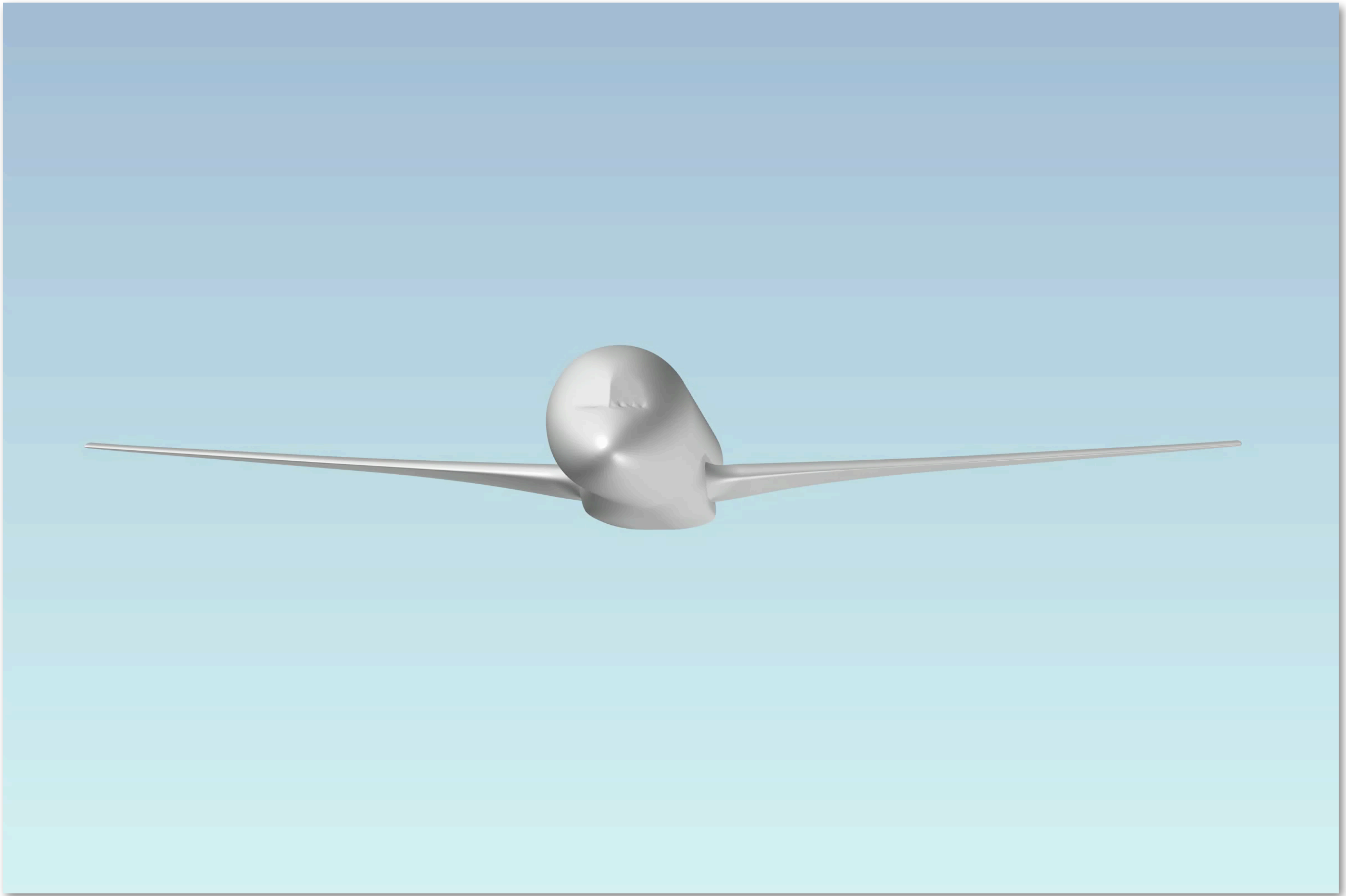
Modeling the VCCTEF

- Flap deflections controlled by Blender "armature," which is analagous to a skeleton
- Surface triangulation is bound to "bones"
- Bones can only rotate about hinge lines
- Sequential flaps bones linked to each other
- Blended transition between flaps to mimic elastomer material





Modeling the VCCTEF with Blender



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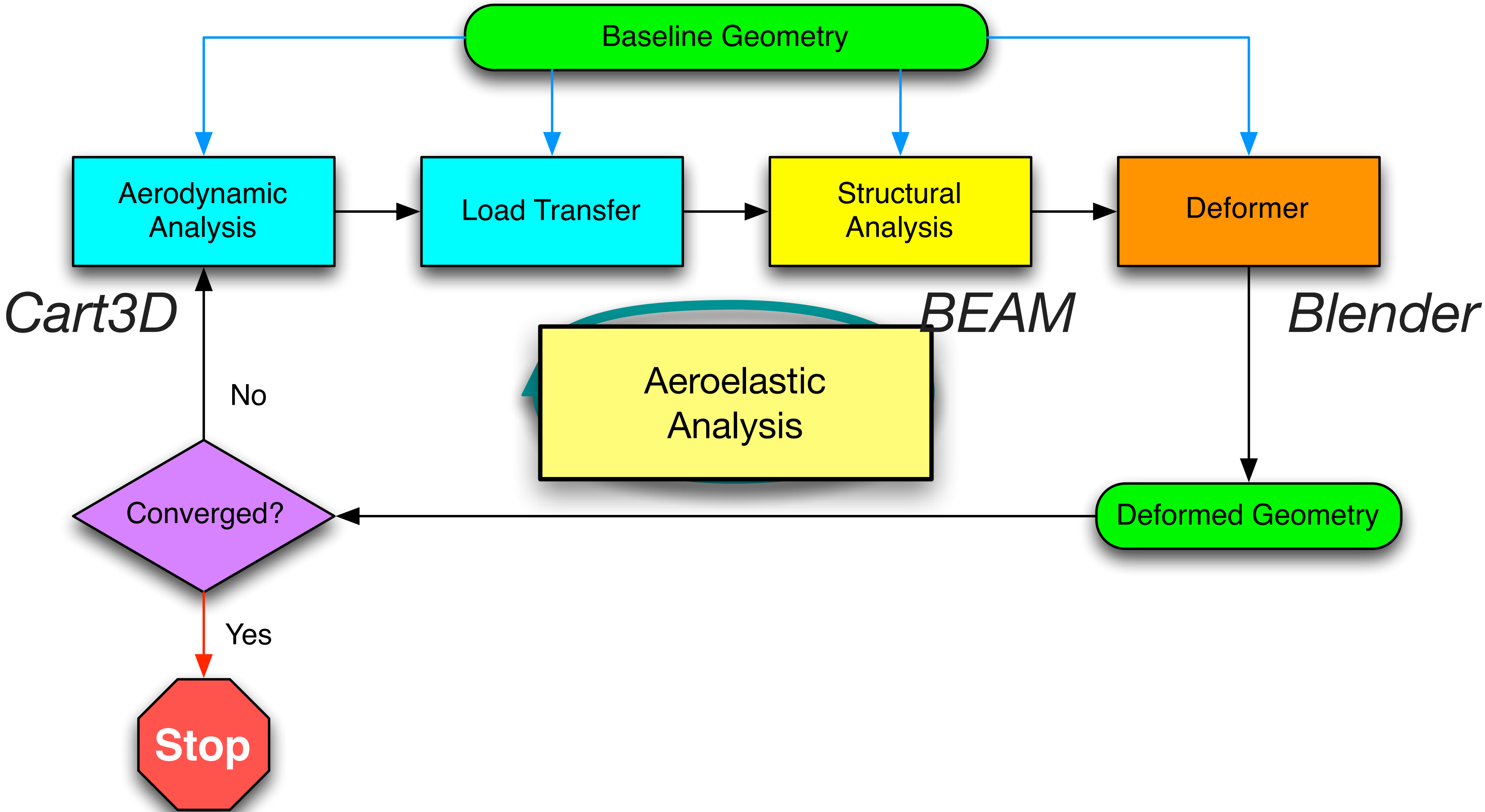
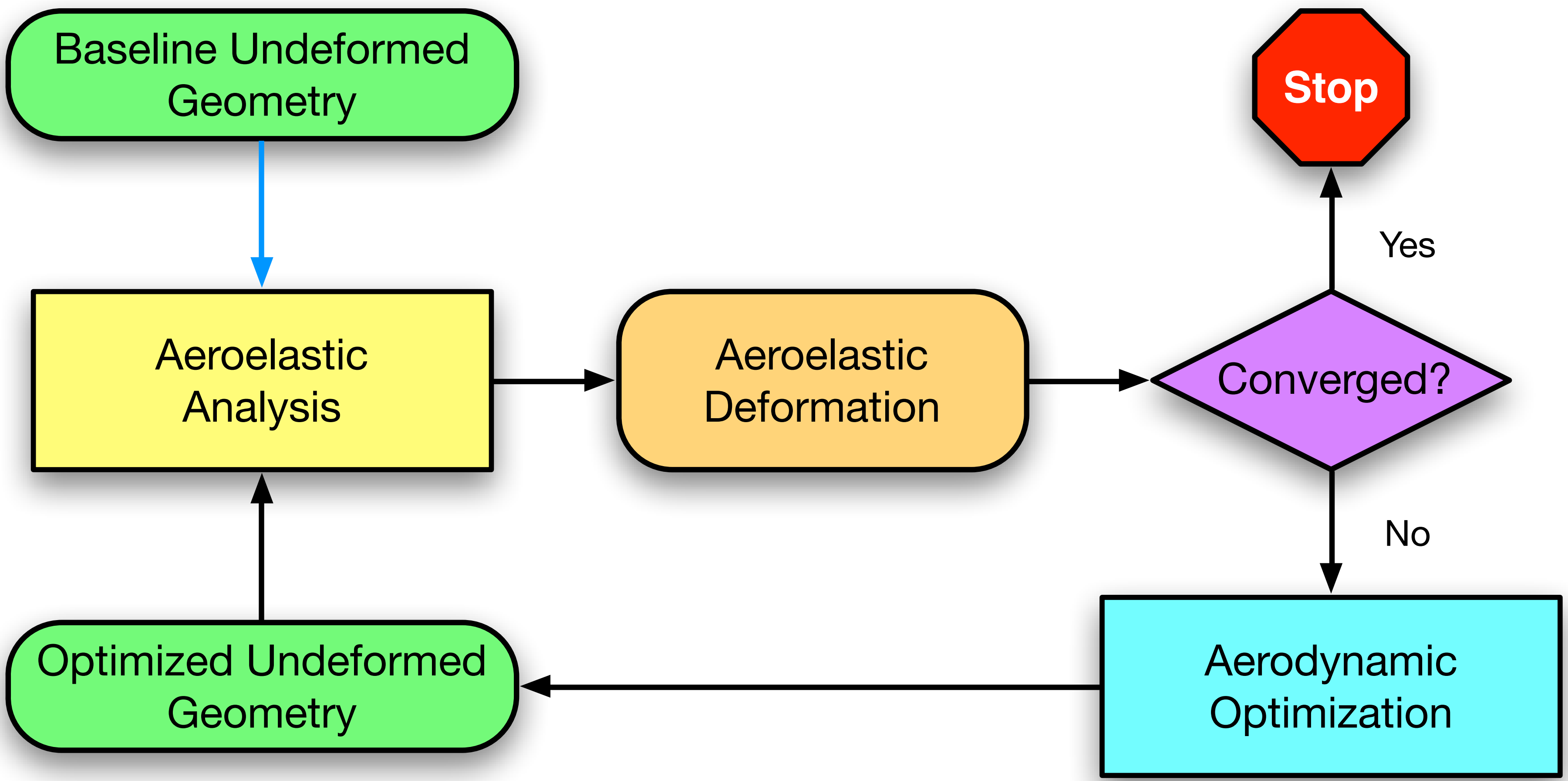
  - aerodynamic evaluation sufficient
  - other design features neglected or held constant (structural weight and layout, trim, actuator weight, viscous effects)
  - for simplicity, work with wing and fuselage only
- Must include aeroelastic effects in analysis
  - conventionally “stiff” wing
  - modern, highly flexible, “soft” wing
- Develop methodology for designing (optimizing) transport wings while addressing aeroelastic effects

Static Aeroelastic Analysis Architecture

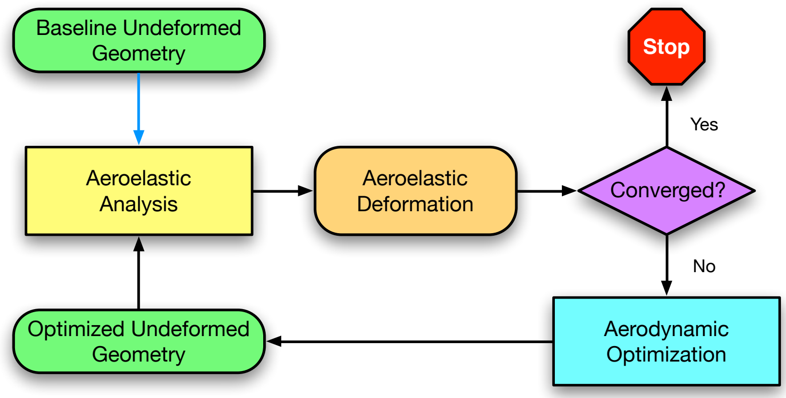


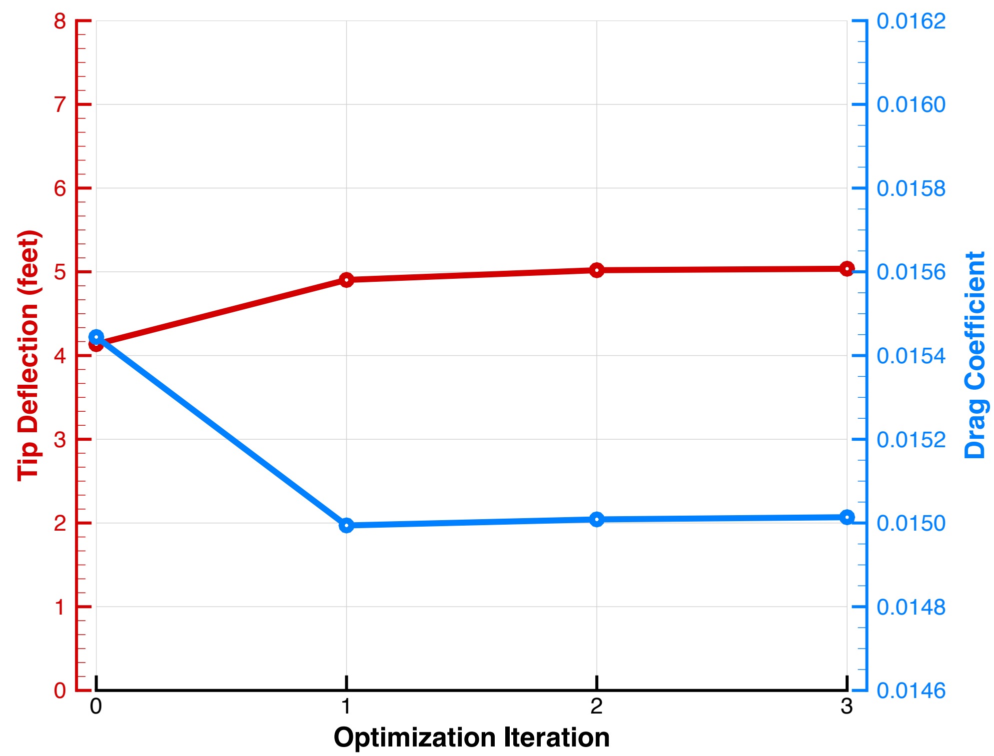
Aerodynamic Shape Optimization Architecture



Performance of Optimization Method

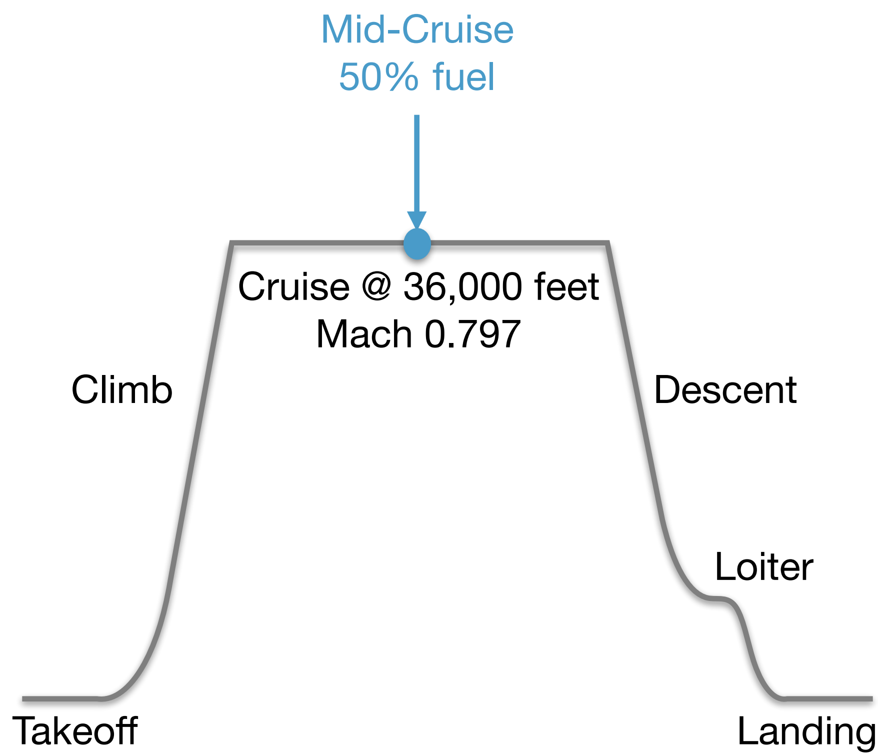
- Alternating aeroelastic analyses and aerodynamic optimizations
  - aeroelastic analysis required 5 iterations
  - typical optimization required 60-80 design space samples
- Typical aeroelastic optimization
  - converges in 3-4 iterations
  - one iteration ≈ 1 day of wall clock time on 64-cpus of *endeavour*





Problem Setup

1. Establish a new baseline for mid-cruise
   - aerodynamic optimization of GTM wing with VCCTEF
   - include aeroelastic effects
   - disregard other disciplines



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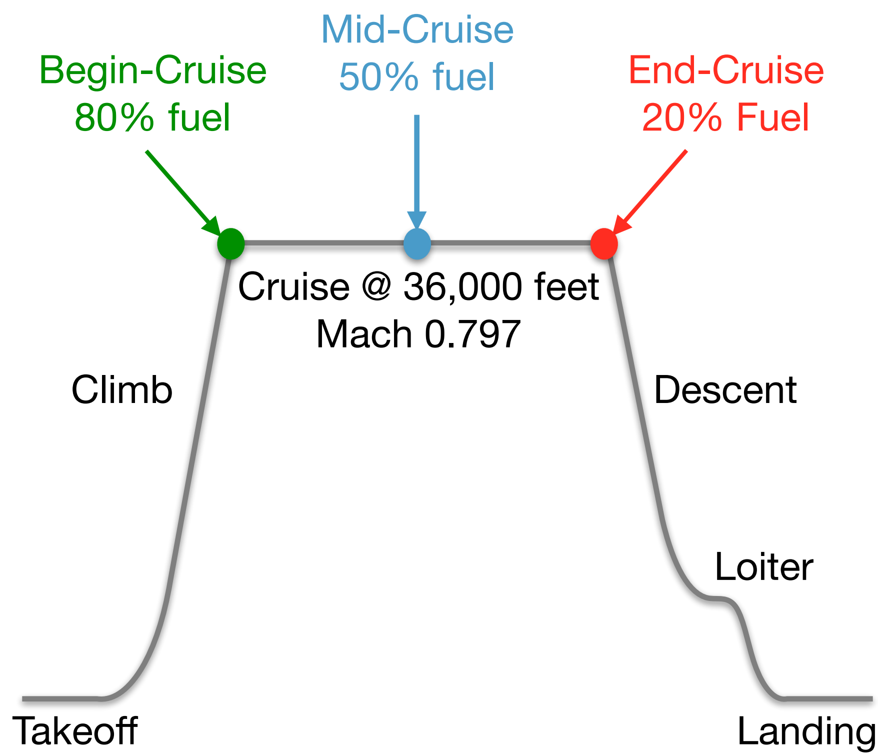
2. Re-design for off-design
    - repeat optimization at begin and end cruise
    - determines best possible performance at off-design conditions



Problem Setup

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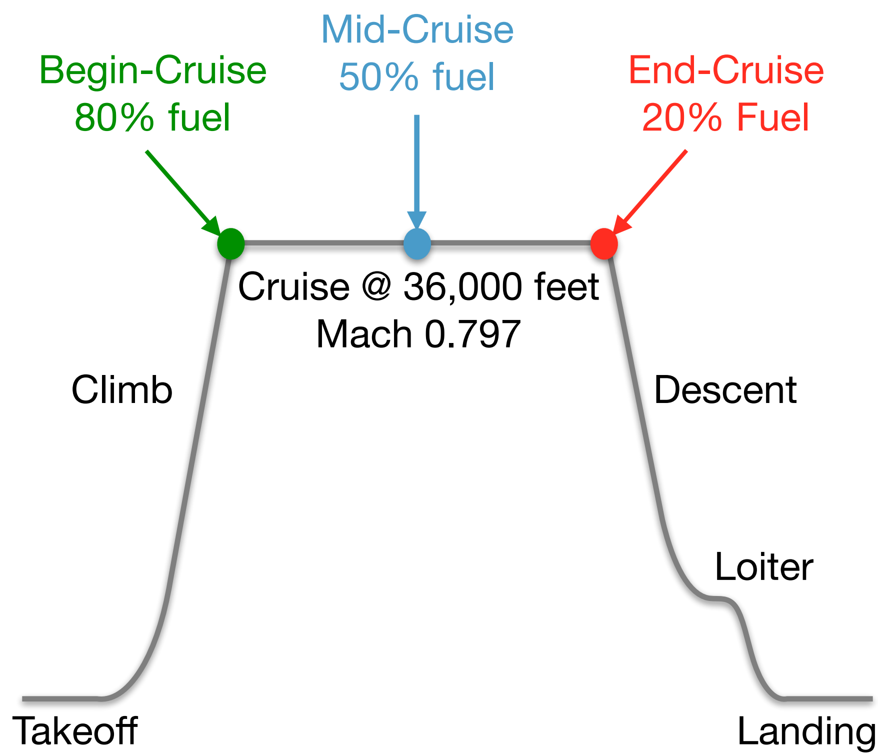
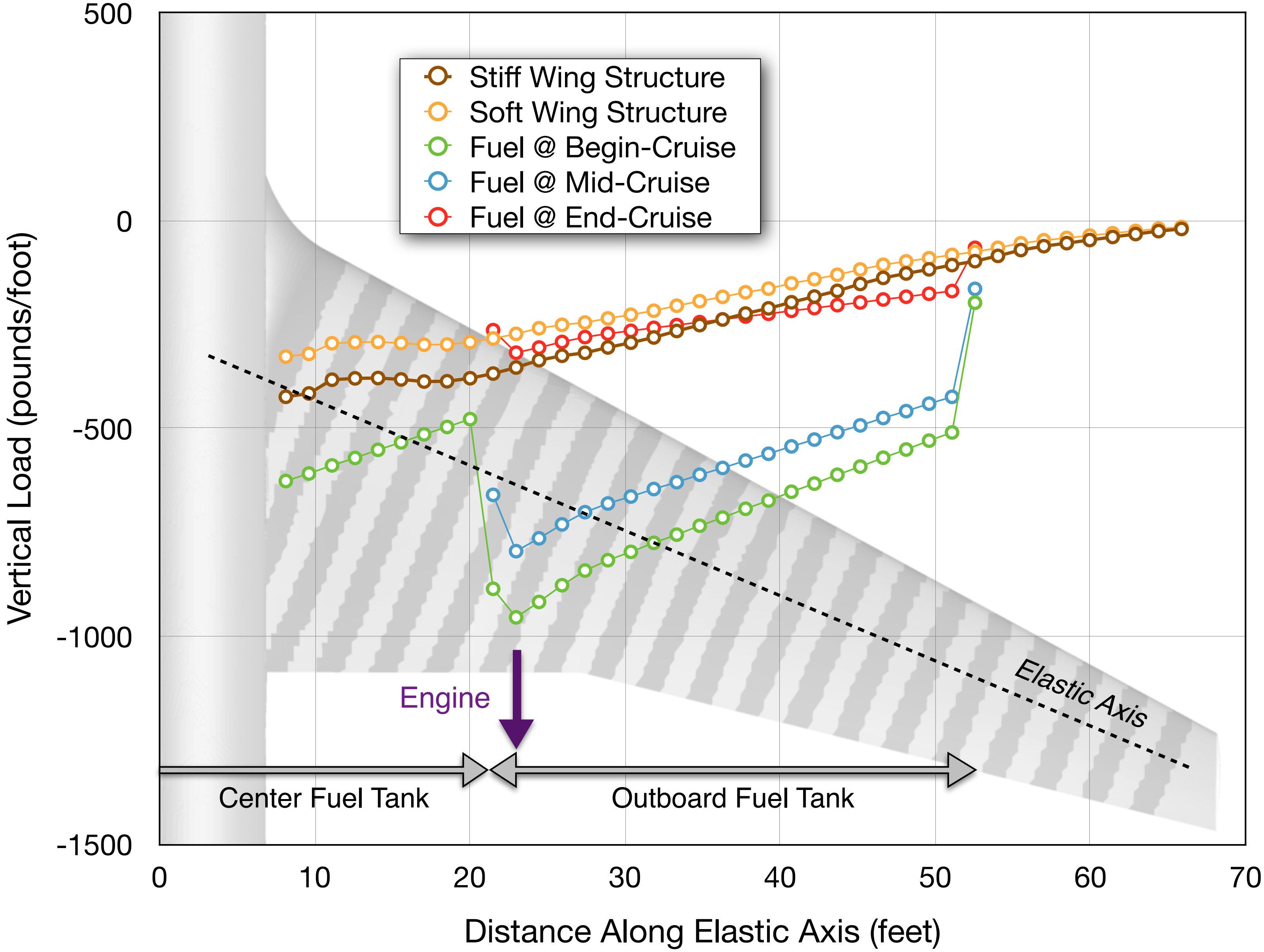
    - aerodynamic optimization of GTM wing with VCCTEF
    - include aeroelastic effects
    - disregard other disciplines
2. Re-design for off-design
    - repeat optimization at begin and end cruise
    - determines best possible performance at off-design conditions
3. Adapt flap system on baseline for off-design
    - optimize only flaps while maintaining baseline twist
    - compare results with best possible performance from step 2



Load Distributions

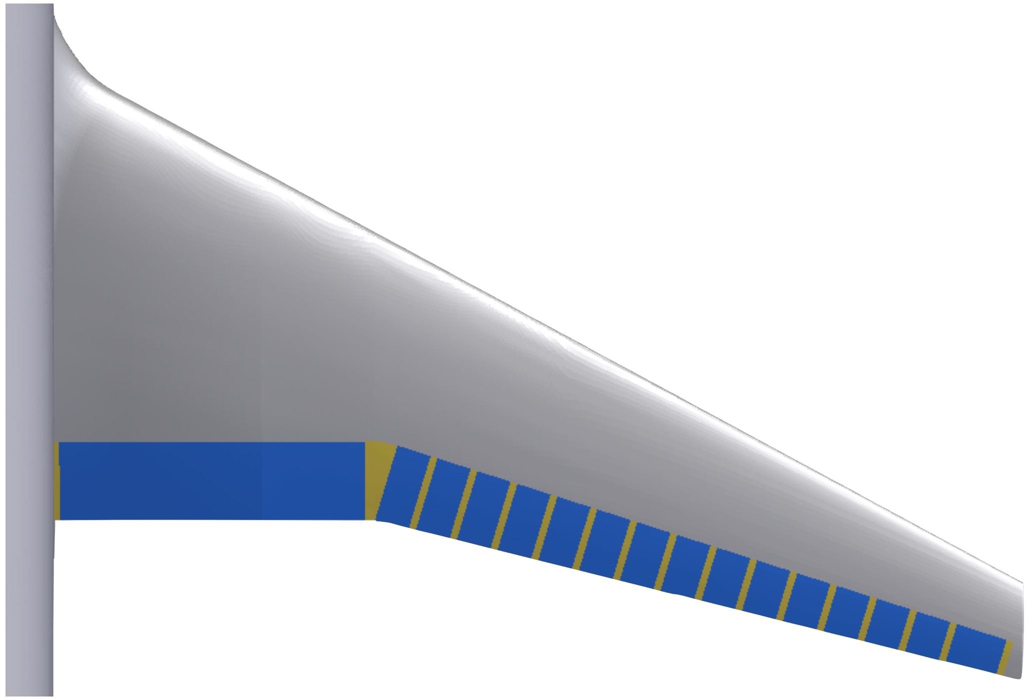


Design Optimization Problem

- Minimize total drag (inviscid)
- Lift is held constant
- Design variables include wing twist and VCCTEF deflections

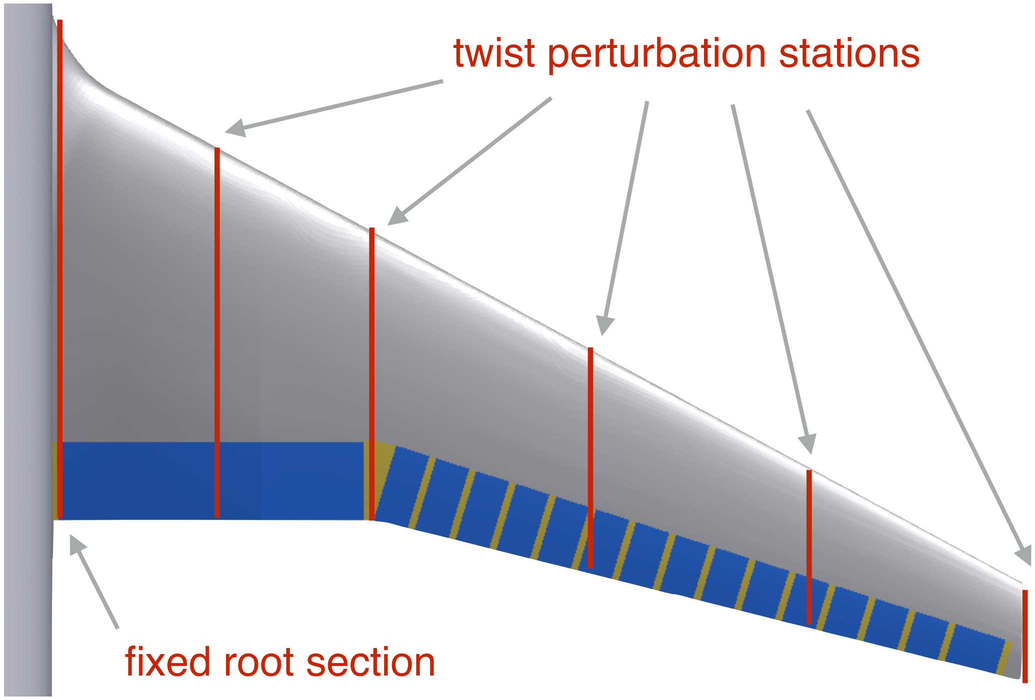
Design Variables

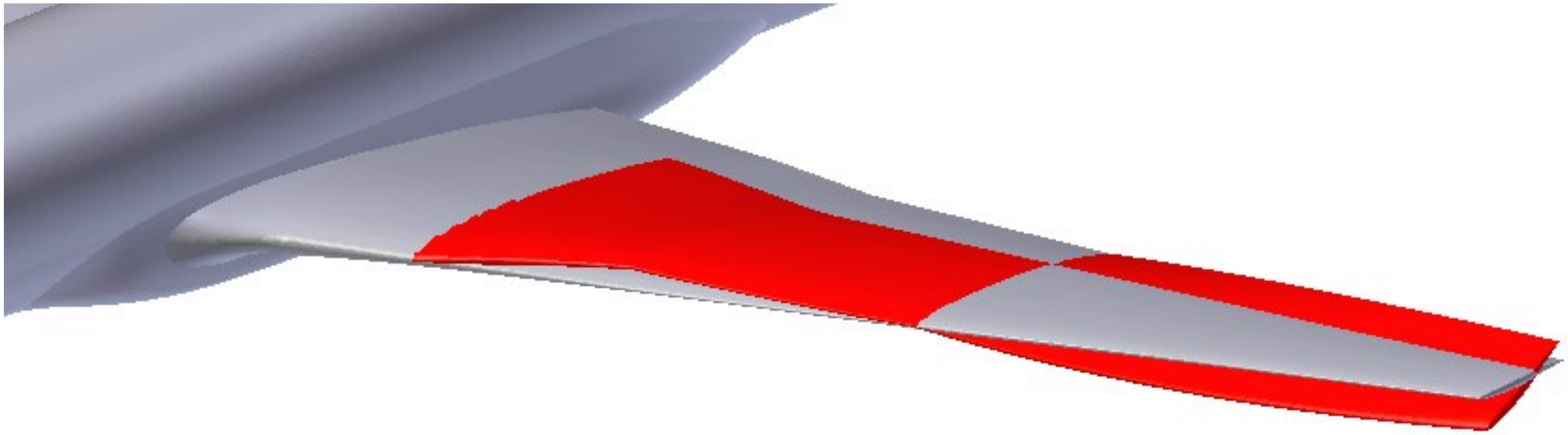
- Angle of attack



Design Variables

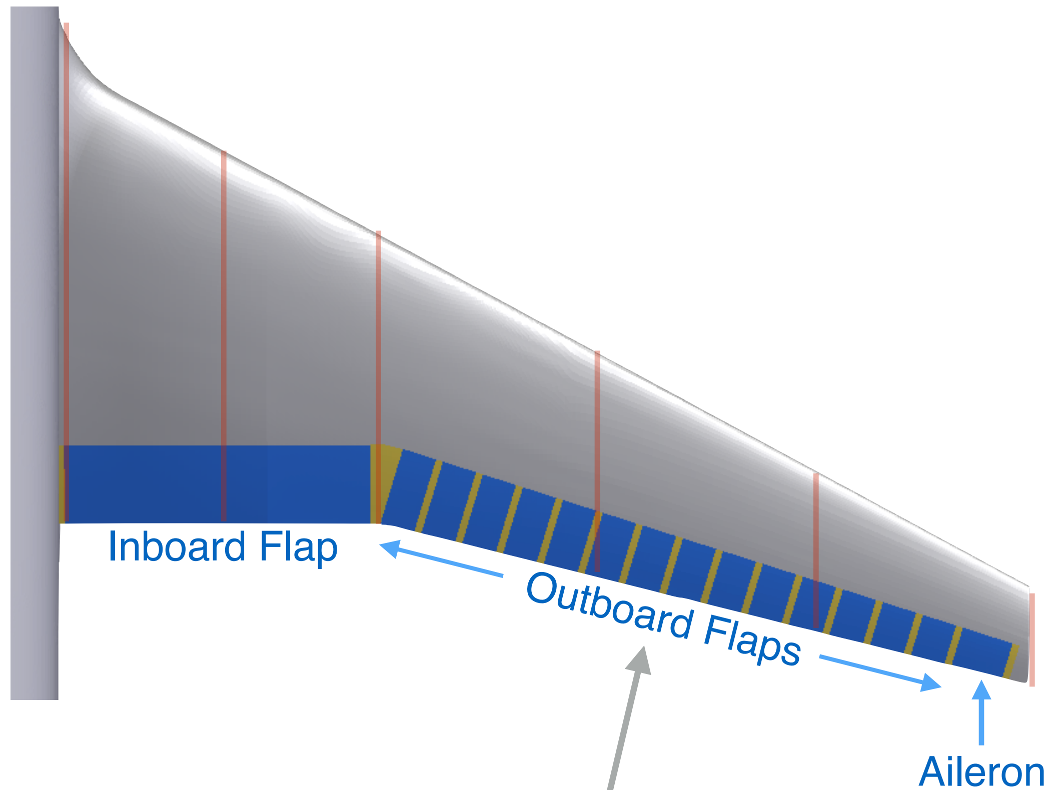
- Angle of attack
- Wing twist distribution
  - modeled as perturbation to original
  - Blender module

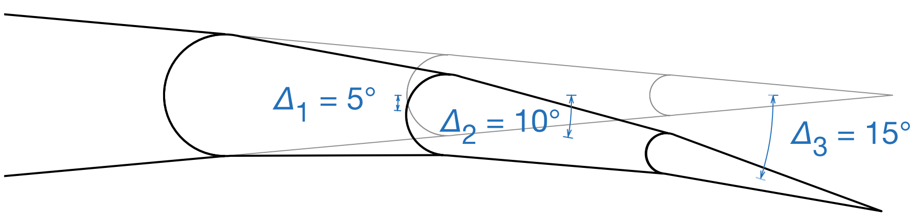




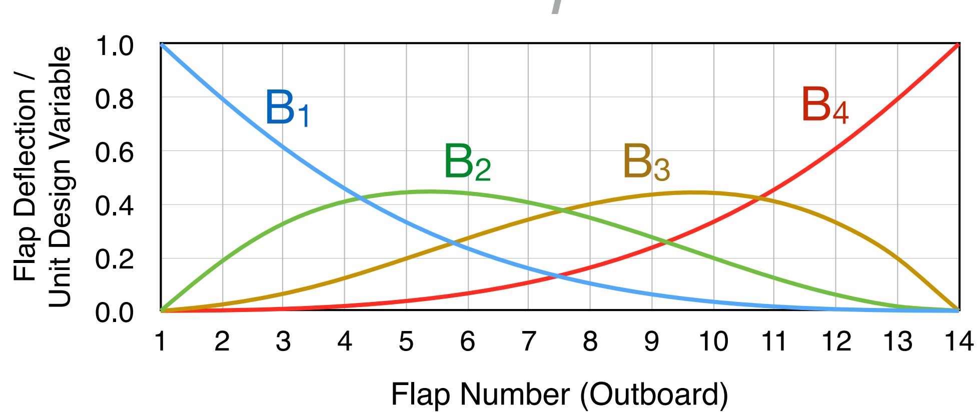
Design Variables

- Angle of attack
- Wing twist distribution
  - modeled as perturbation to original
  - Blender module
- VCCTEF deflections
  - link segments via "circular deflection"
  - Bernstein polynomials for outboard flaps
  - inboard flap and aileron separate



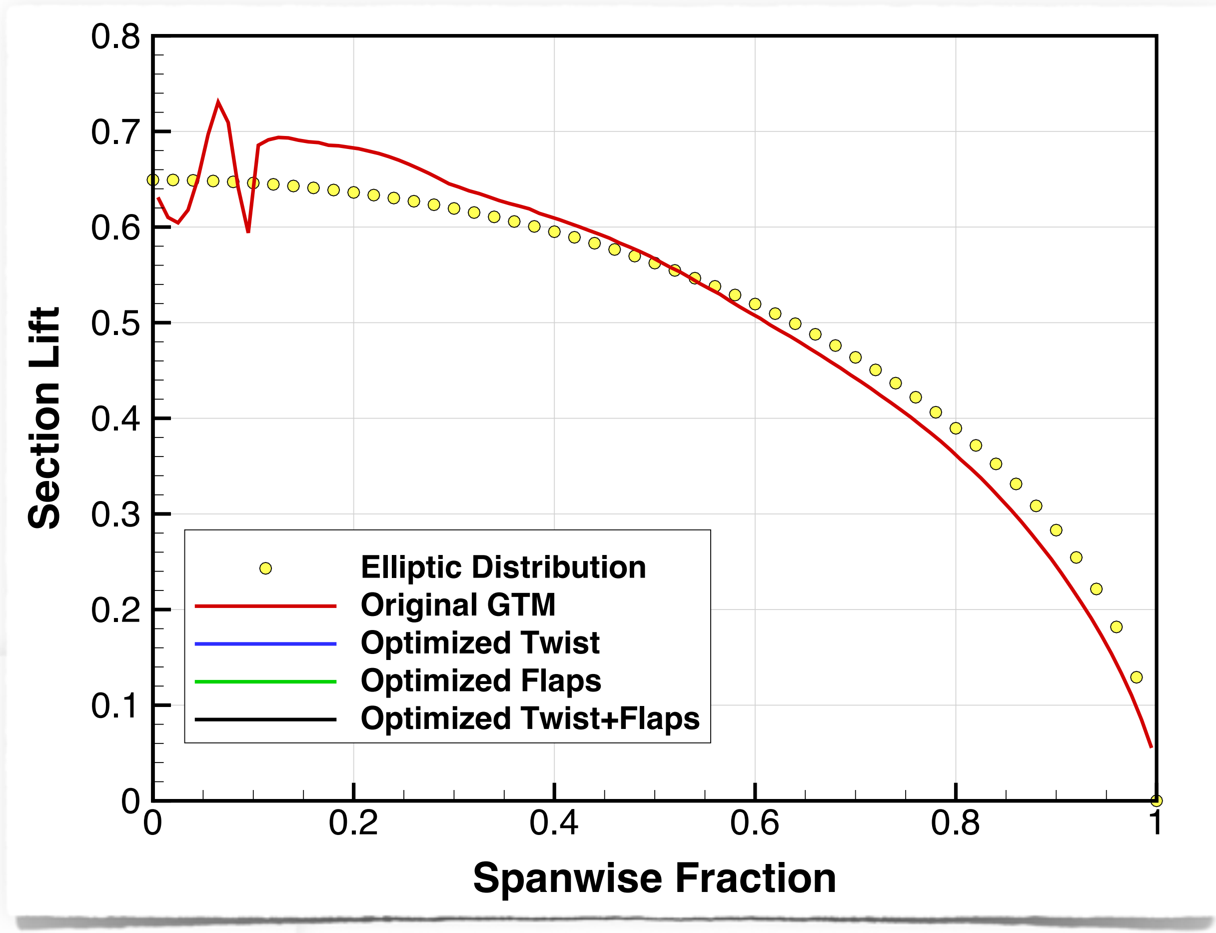


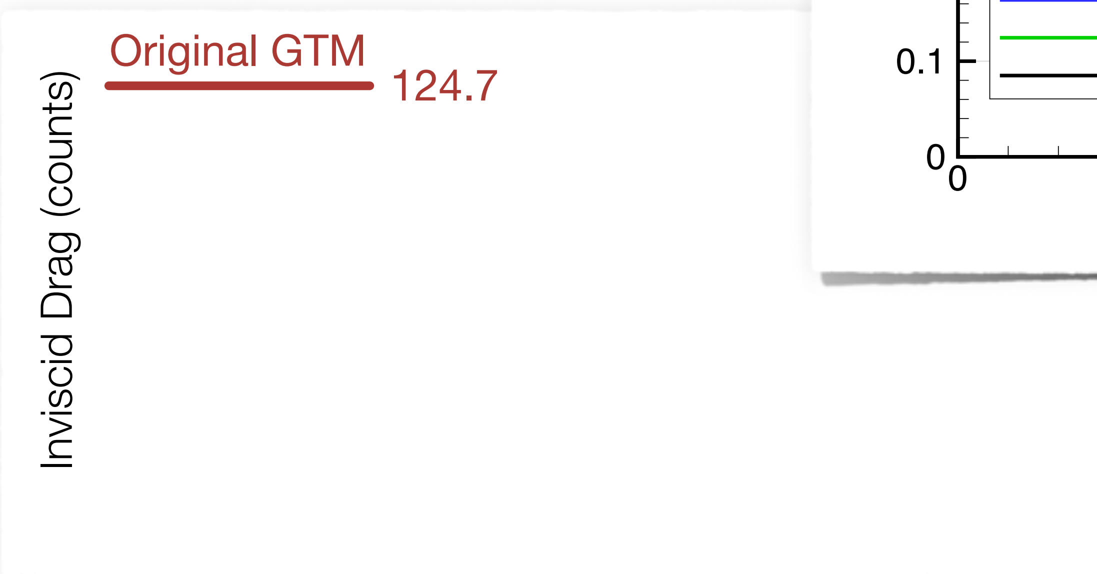
$\Delta_2 = 2\Delta_1$, $\Delta_3 = 3\Delta_1$



Stiff Wing Optimization and Analysis (Mid-Cruise)

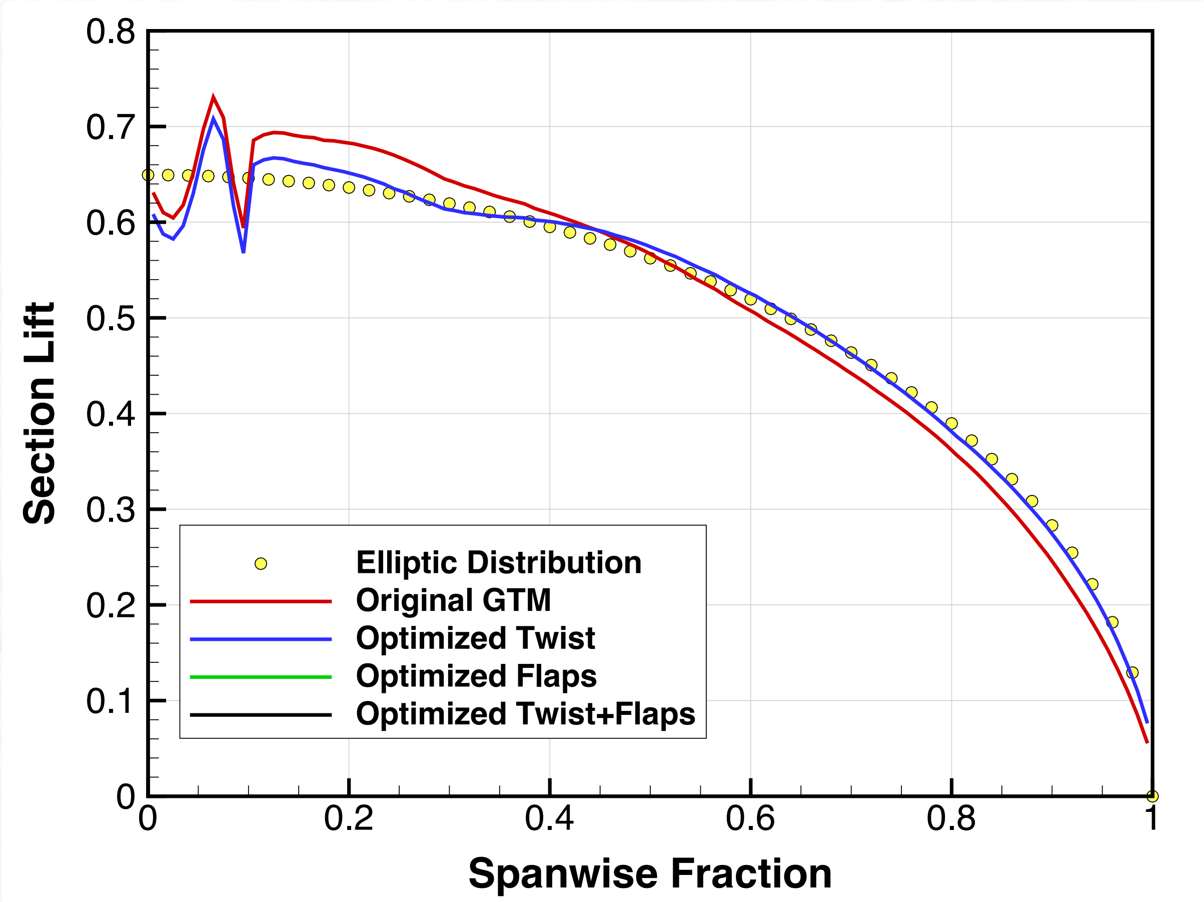
- Start with original GTM

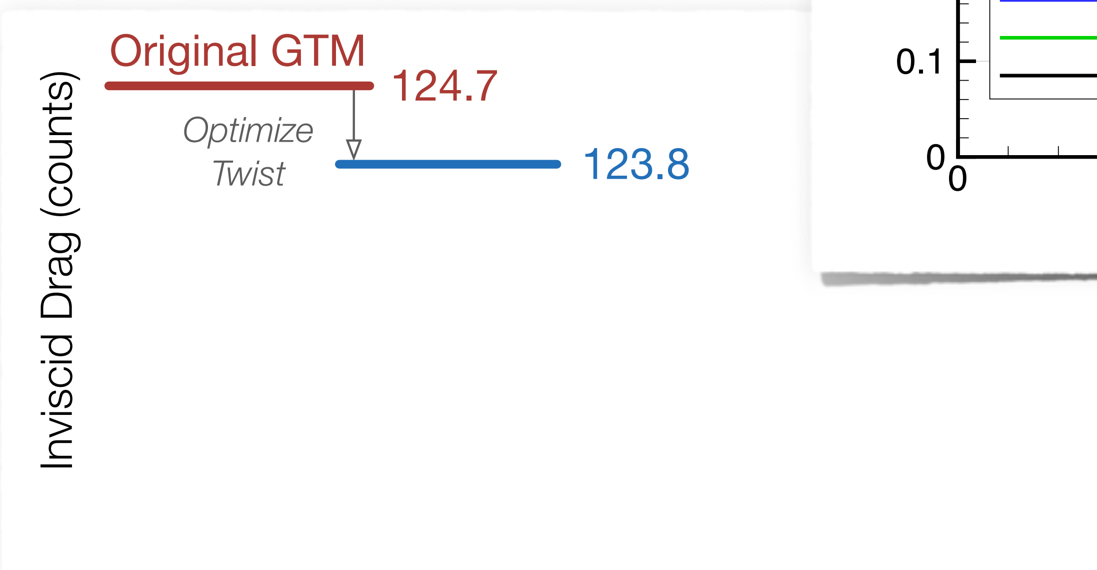




Stiff Wing Optimization and Analysis (Mid-Cruise)

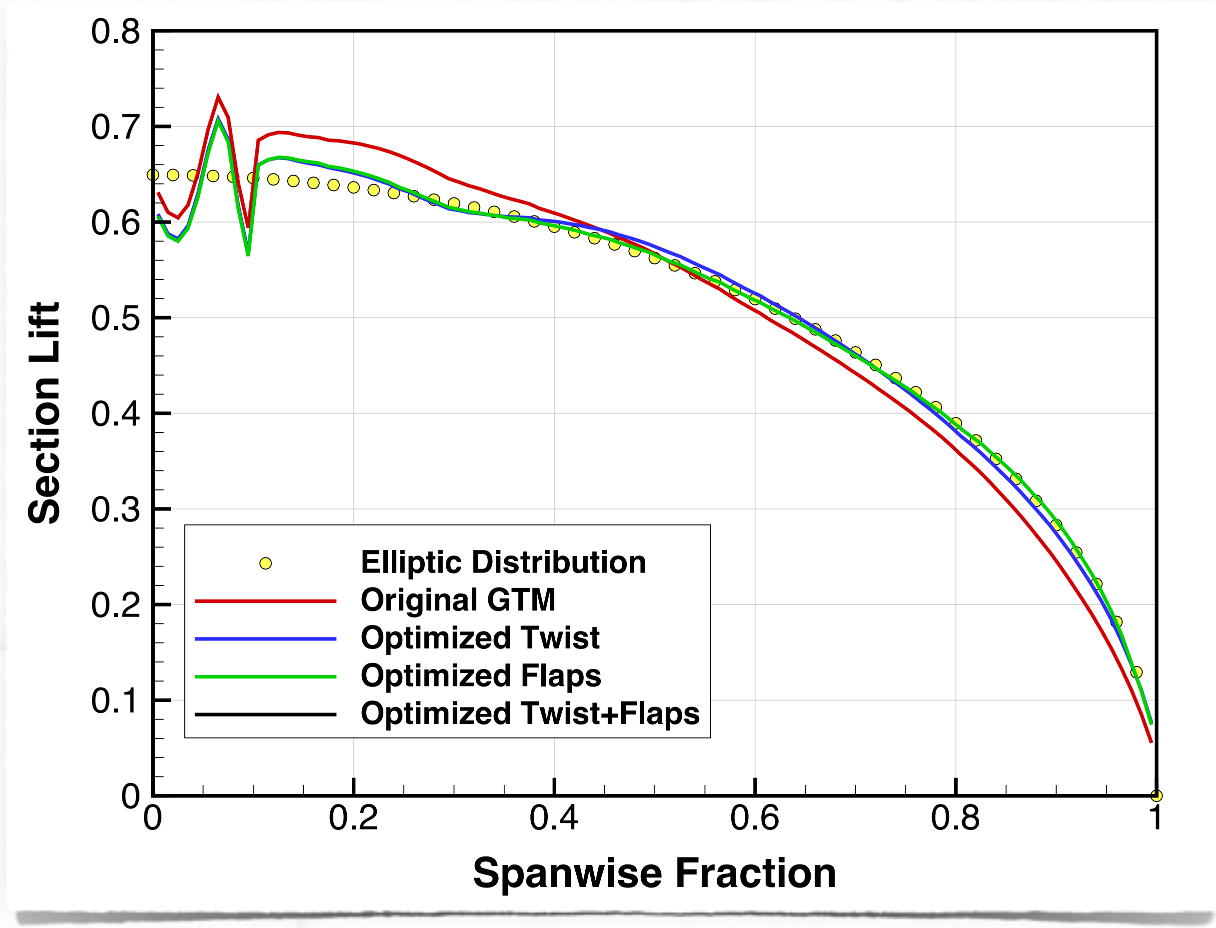
- Start with original GTM
- Optimize twist

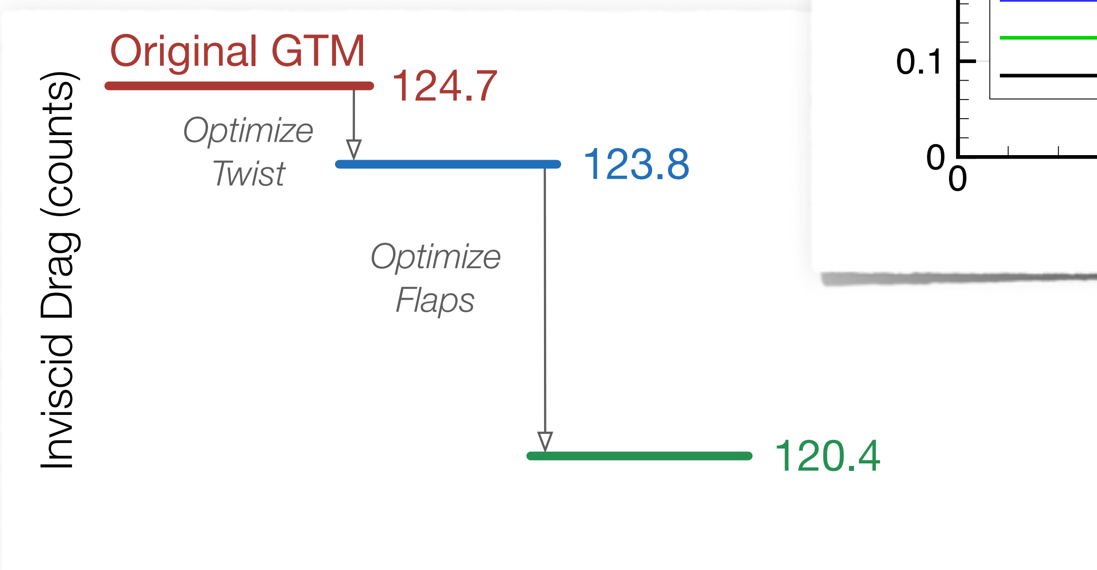




Stiff Wing Optimization and Analysis (Mid-Cruise)

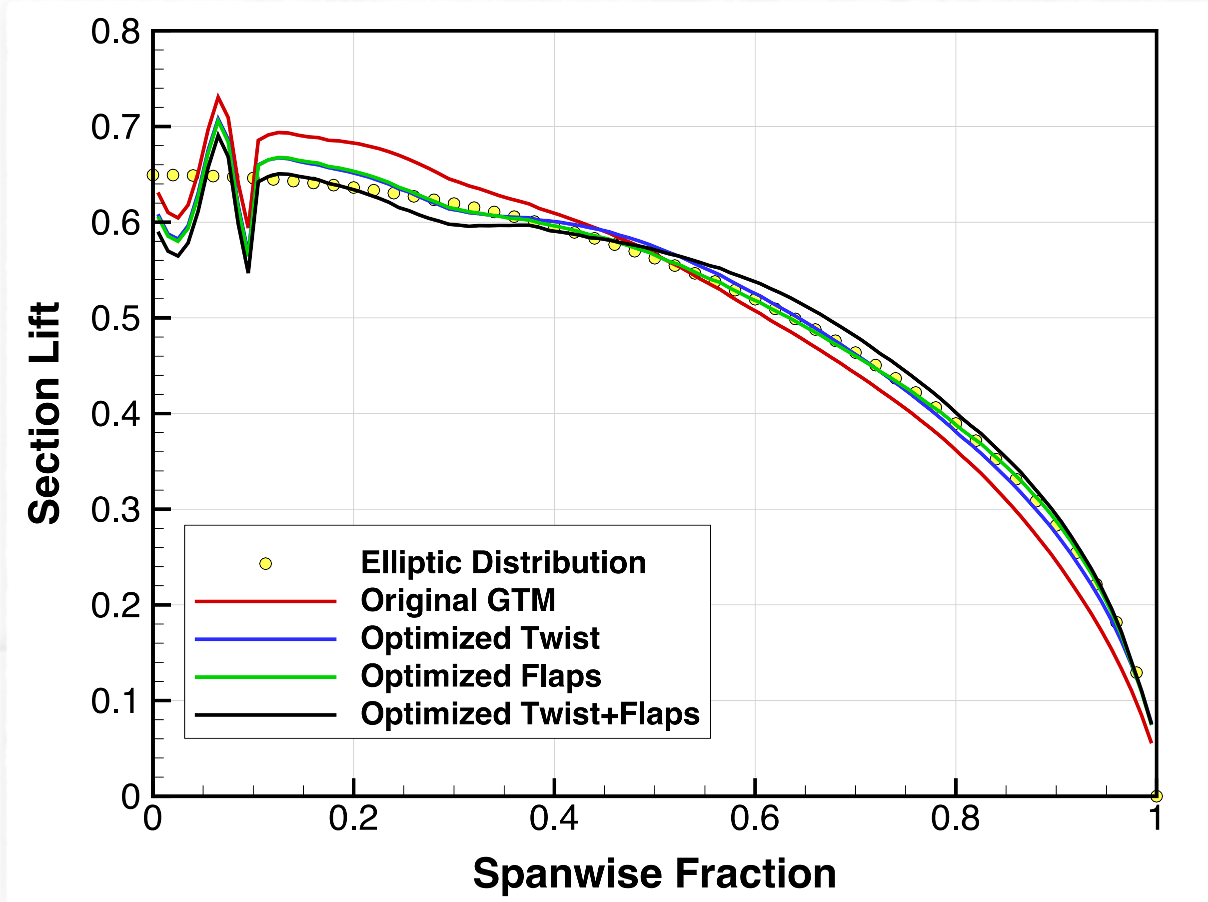
- Start with original GTM
- Optimize twist
- Optimize flaps (fixed twist)

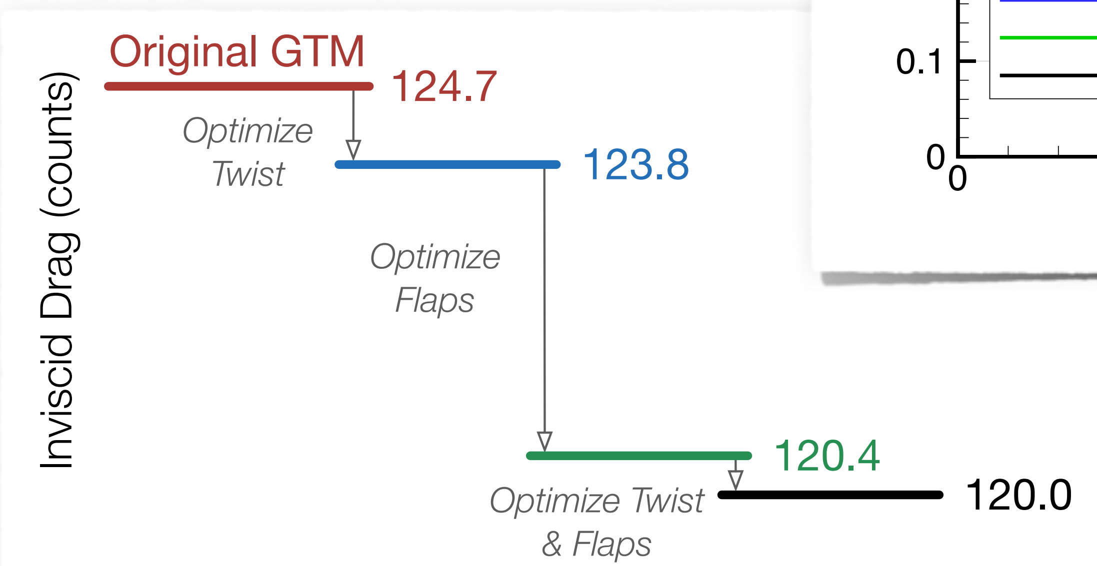




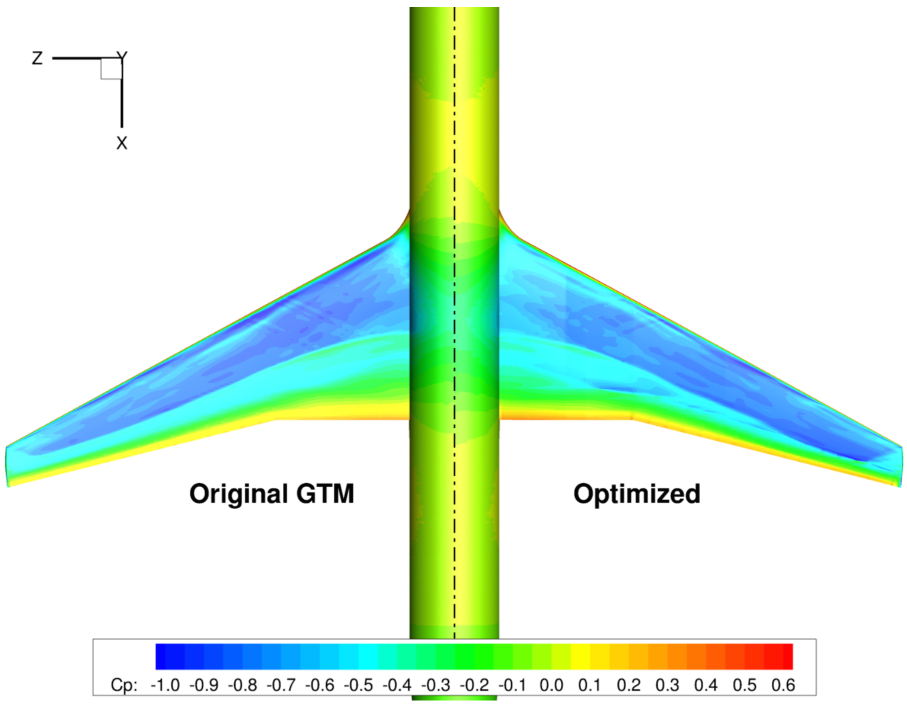
Stiff Wing Optimization and Analysis (Mid-Cruise)

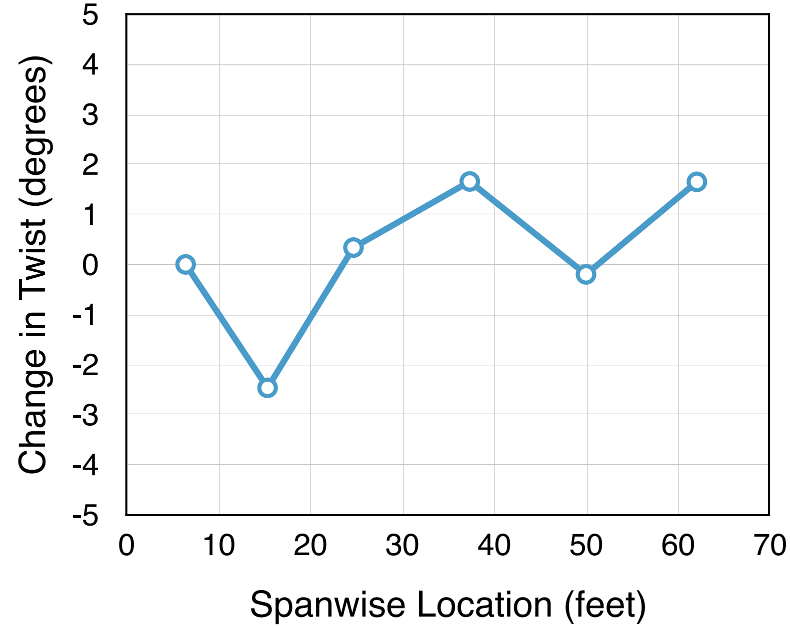
- Start with original GTM
- Optimize twist
- Optimize flaps (fixed twist)
- Optimize twist and flaps

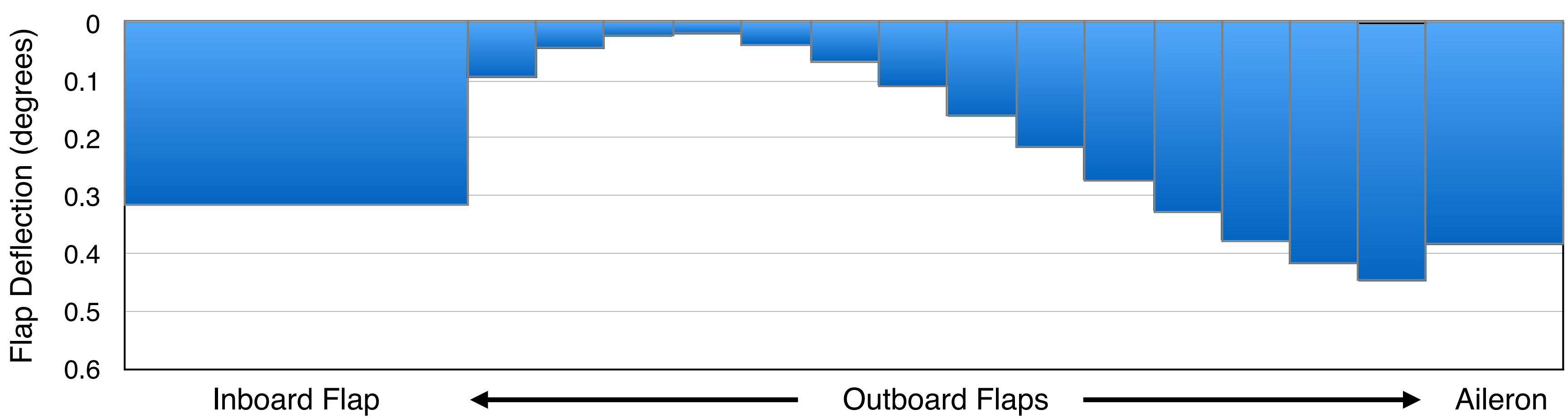




Stiff Wing GTM - Mid-Cruise Optimized

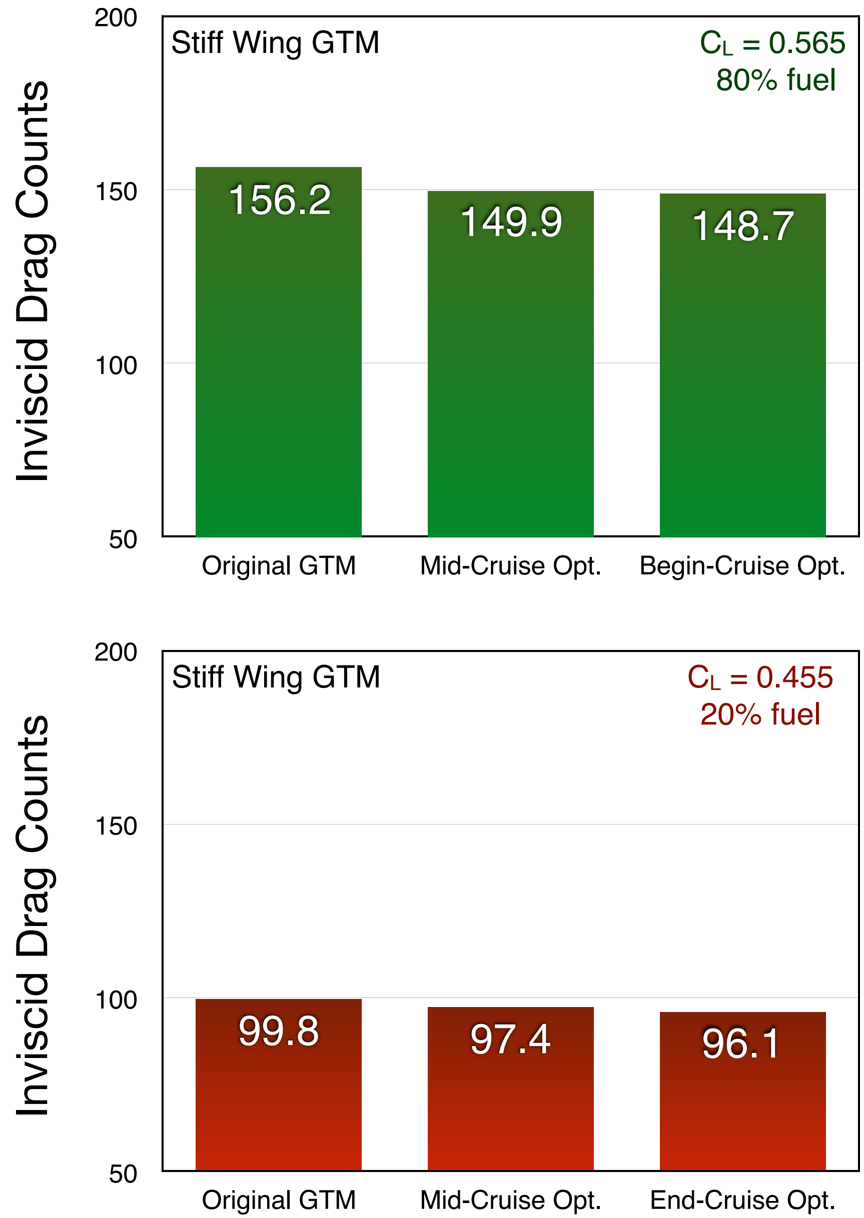






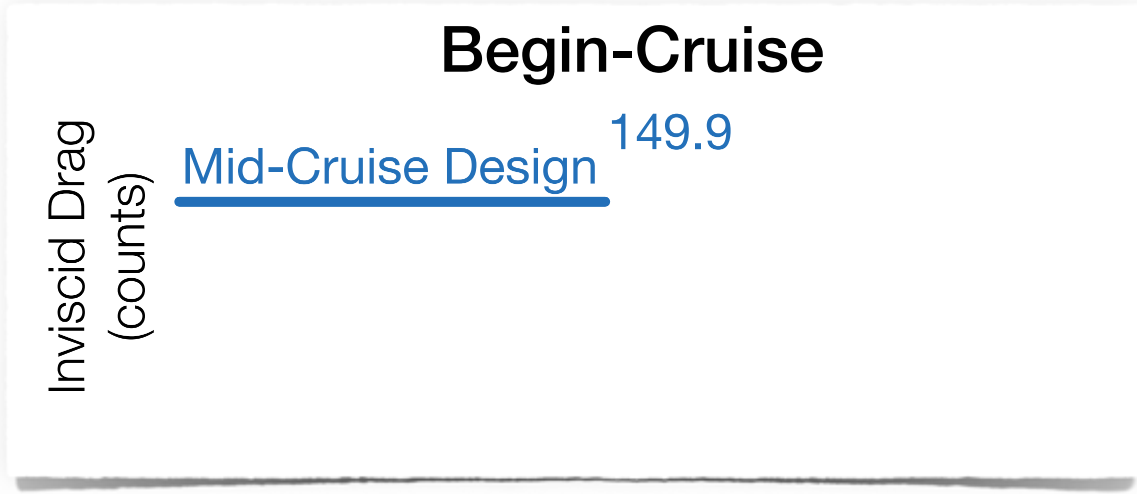
Stiff Wing Off-Design Analysis and Optimization

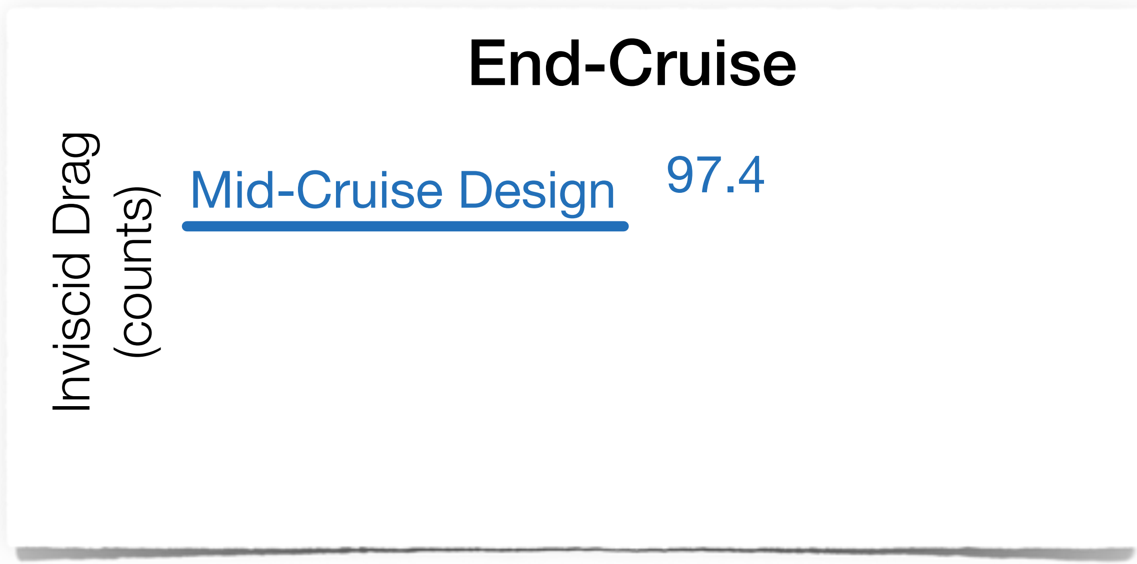
- Analyze wing optimized for mid-cruise at off-design conditions
    - begin-cruise (80% max fuel)
    - end-cruise (20% max fuel)
- Re-optimize wing for the off-design conditions
- Quantify penalty for flying mid-cruise optimized wing at off-design



Stiff GTM Wing - VCCTEF Adaptation

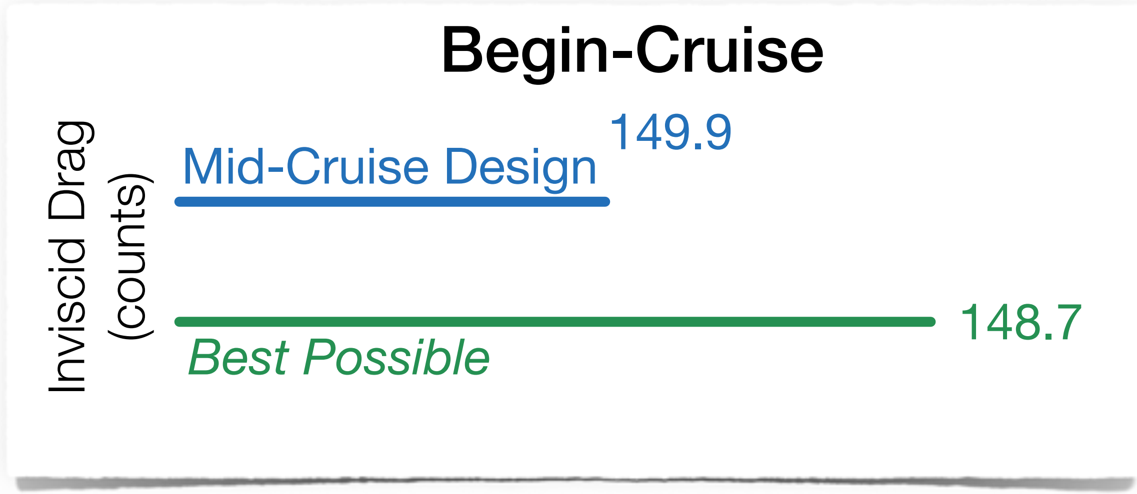
- Start with wing designed for mid-cruise

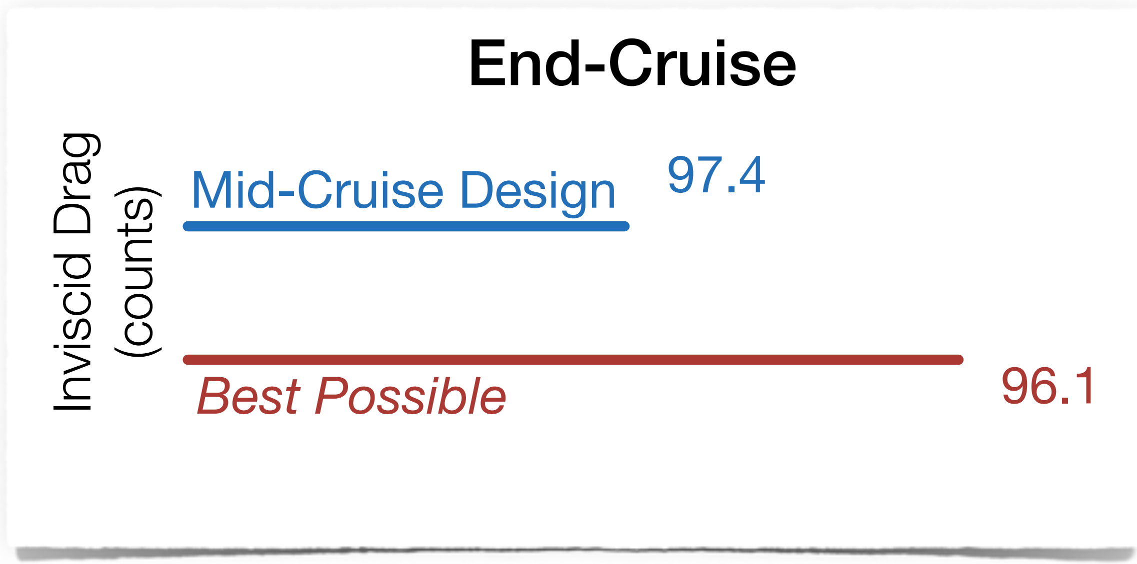




Stiff GTM Wing - VCCTEF Adaptation

- Start with wing designed for mid-cruise
- Compare with wing optimized for off-design condition





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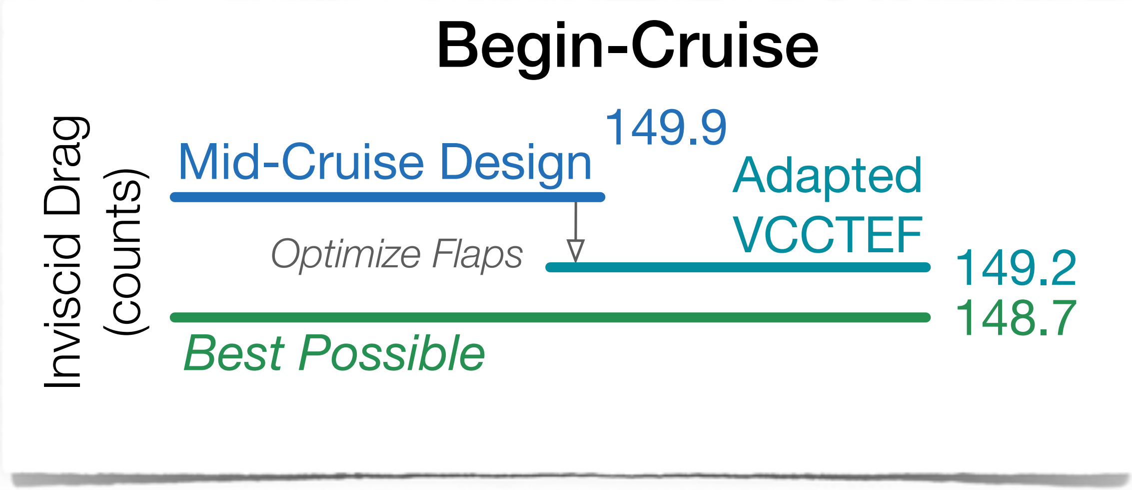
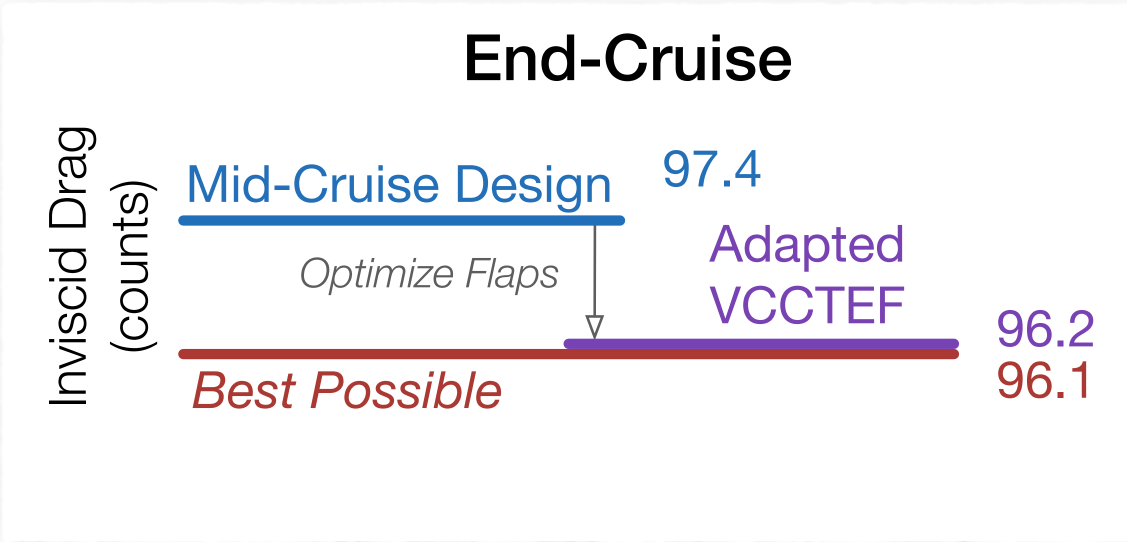
- Start with wing designed for mid-cruise
- Compare with wing optimized for off-design condition
- Optimize VCCTEF deflections to recover lost performance
- Improvement in both cases



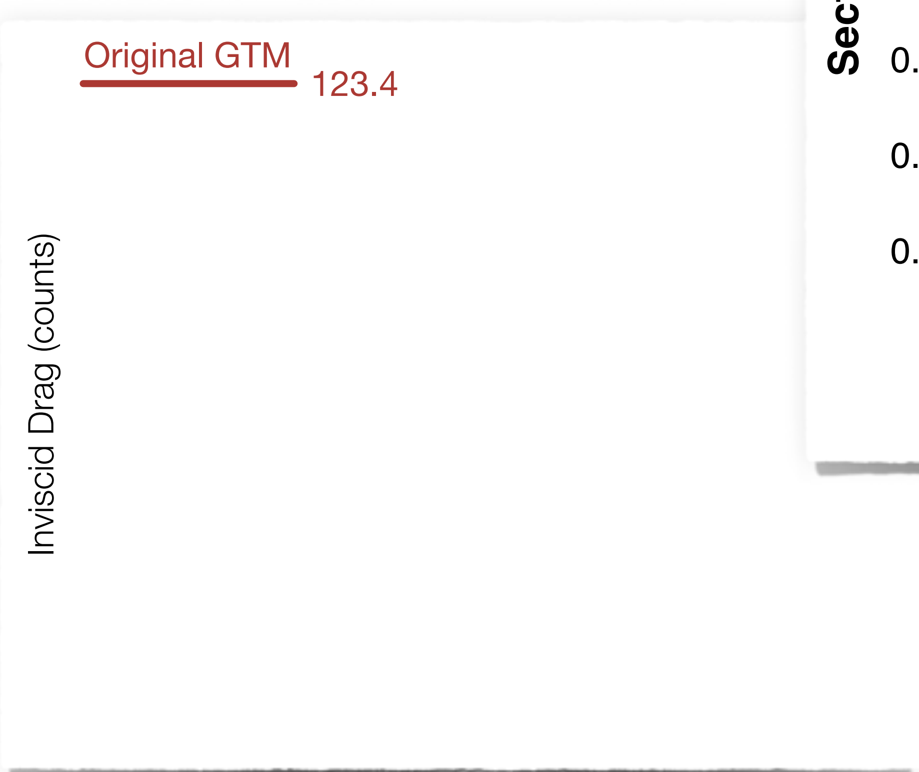


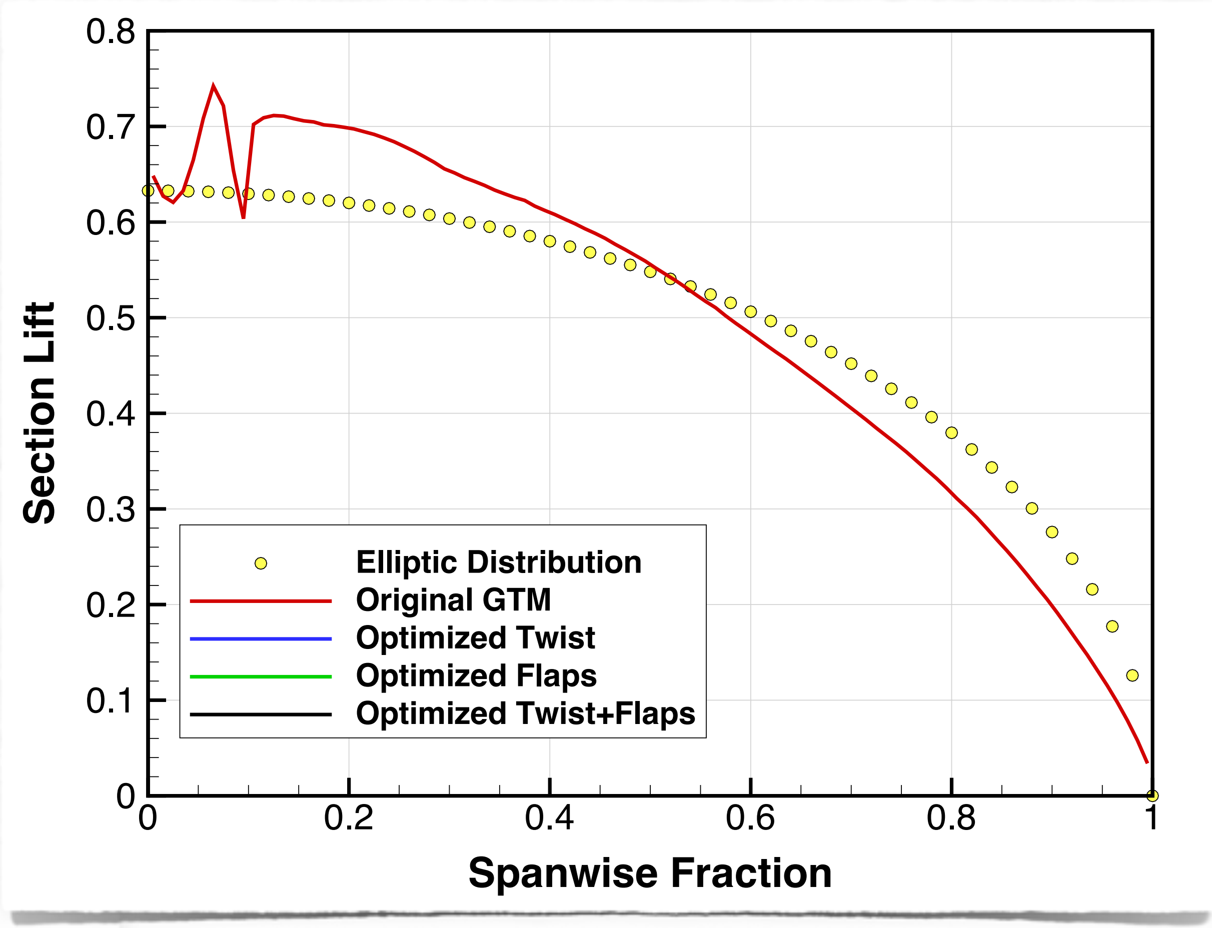
Soft Wing Definition

- Stiff wing used structural model similar to that of actual transport
- Soft wing is defined by halving the bending and torsional stiffness distribution of stiff wing

Soft Wing Optimization and Analysis (Mid-Cruise)

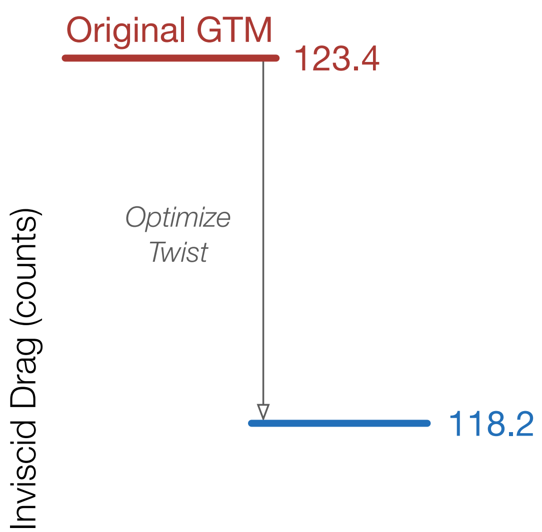
- Start with original GTM

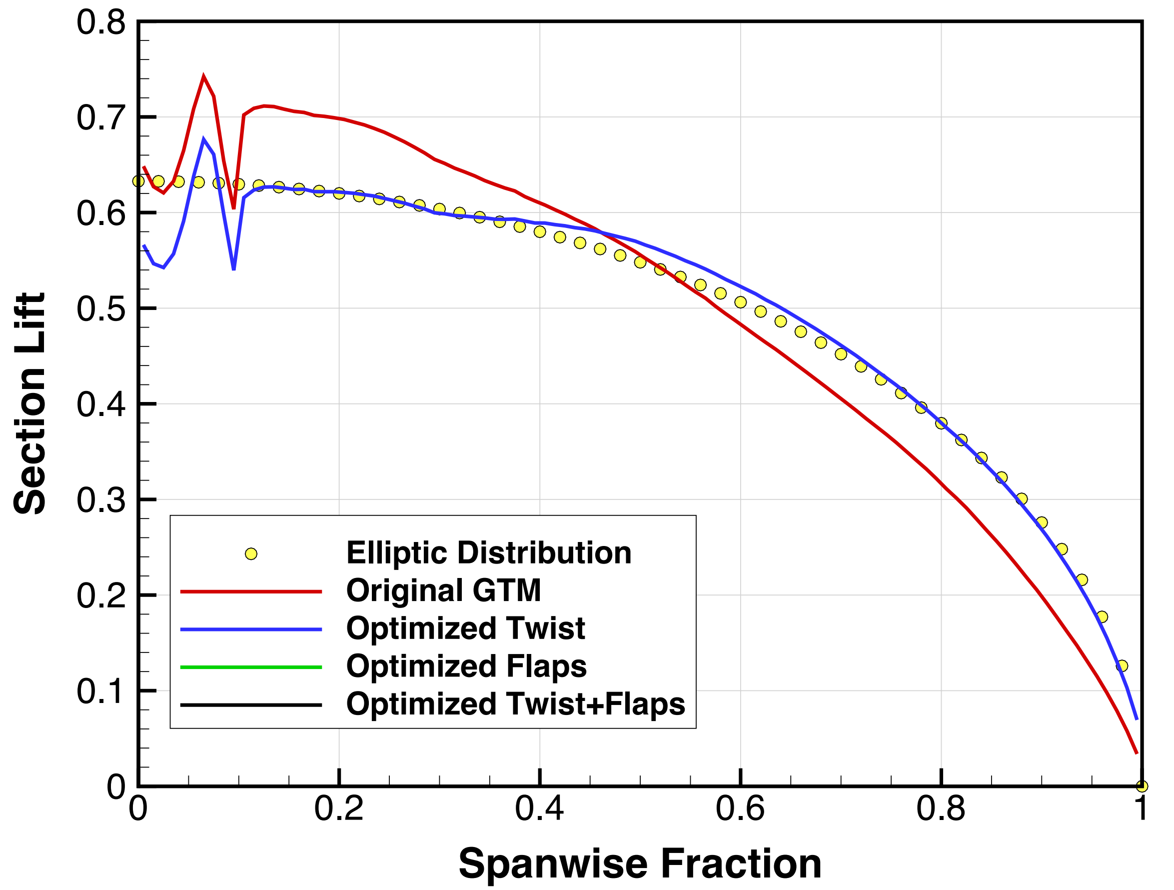




Soft Wing Optimization and Analysis (Mid-Cruise)

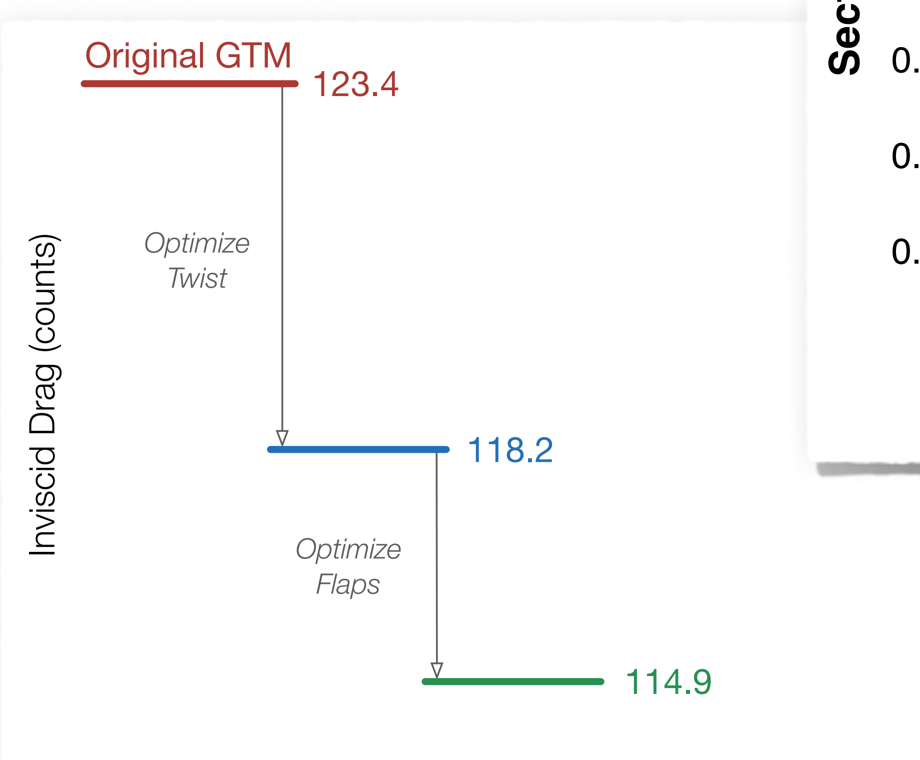
- Start with original GTM
- Optimize twist

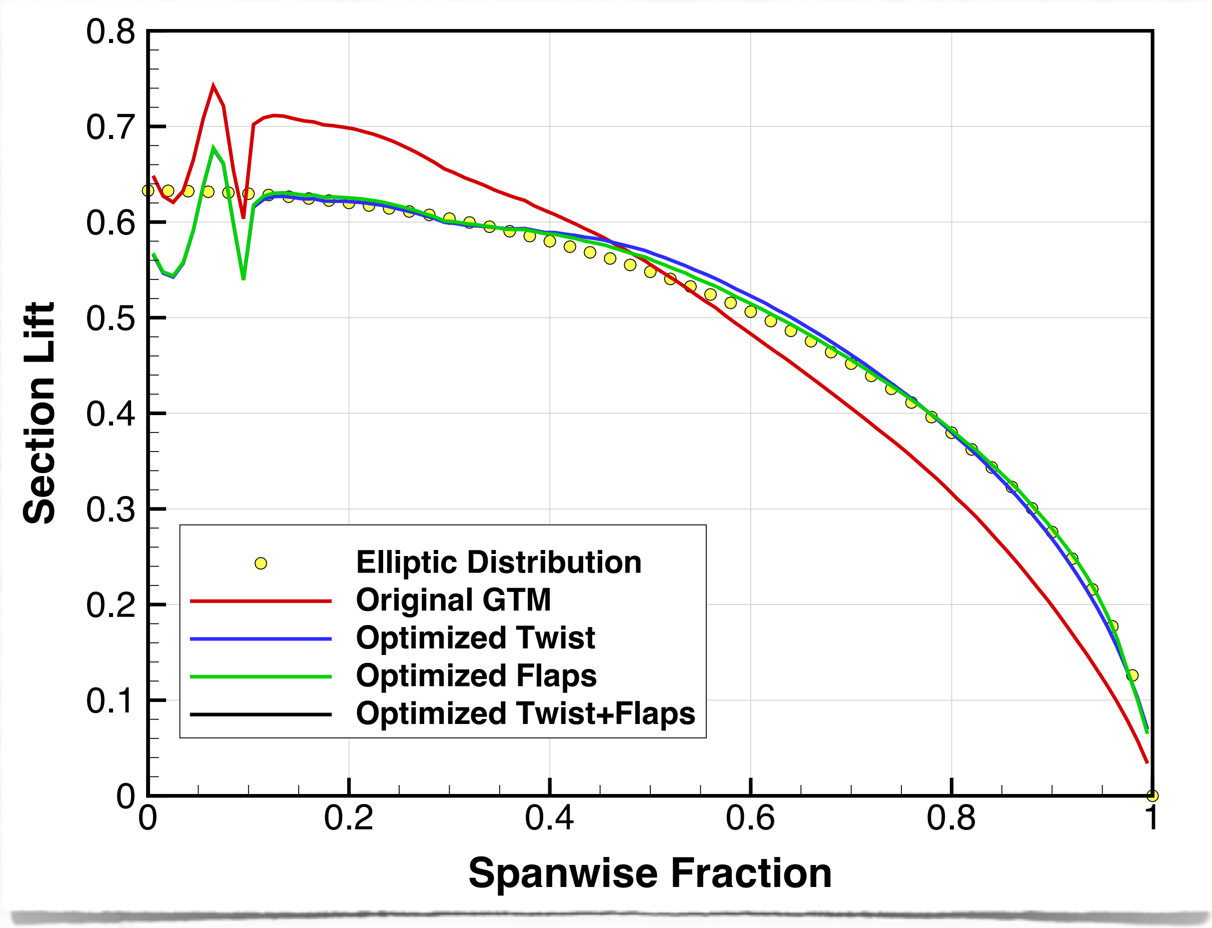




Soft Wing Optimization and Analysis (Mid-Cruise)

- Start with original GTM
- Optimize twist
- Optimize flaps (fixed twist)





Soft Wing Optimization and Analysis (Mid-Cruise)

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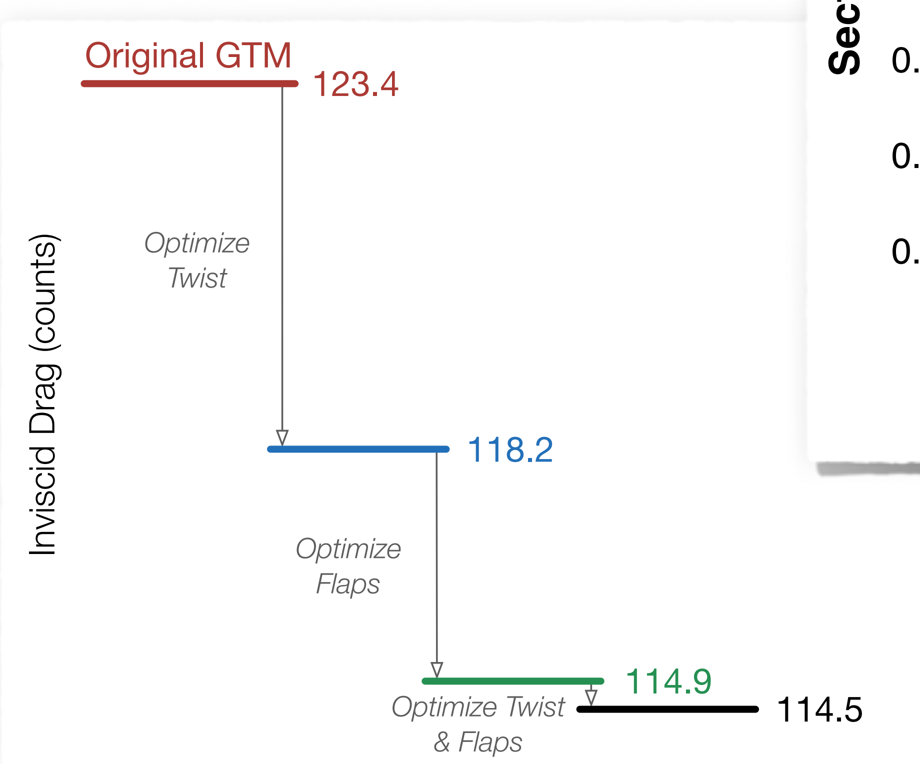
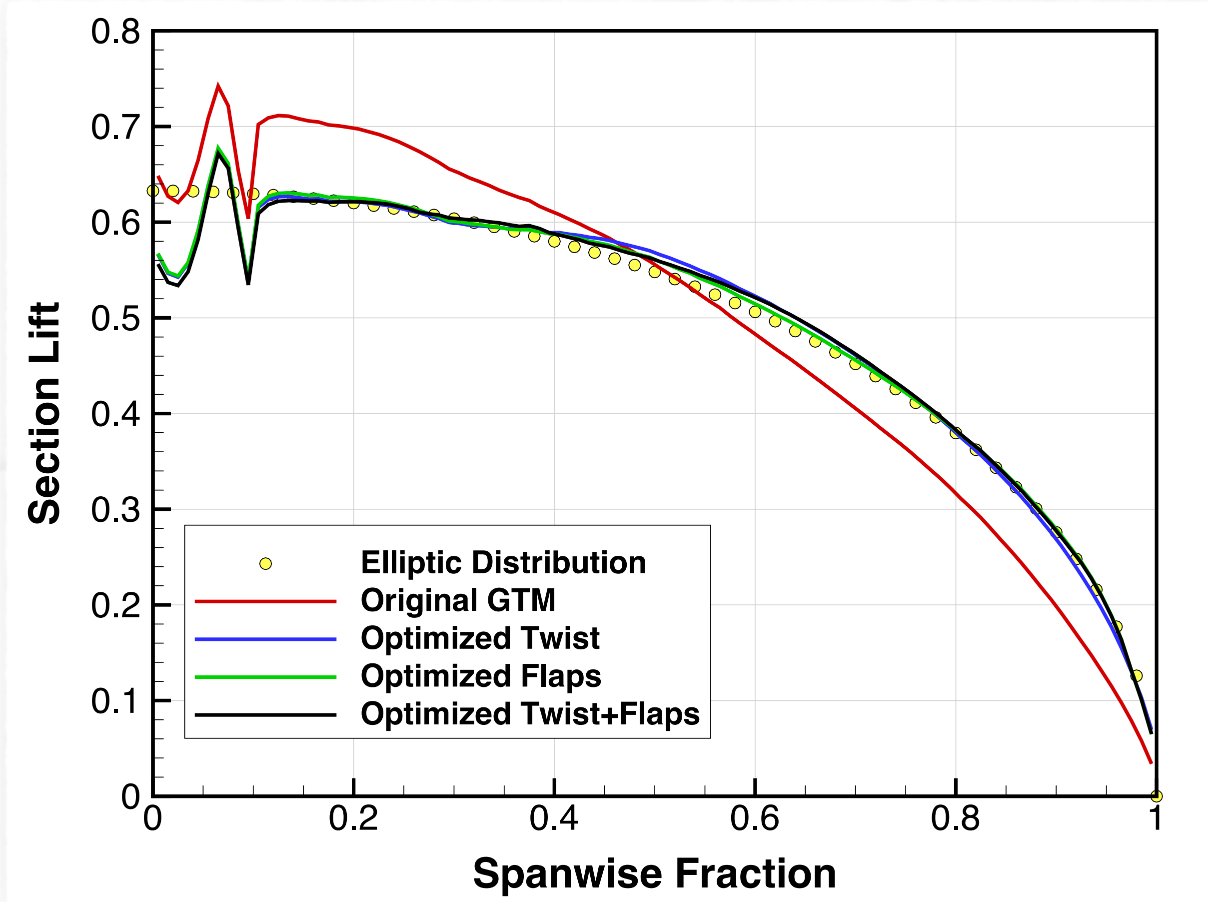
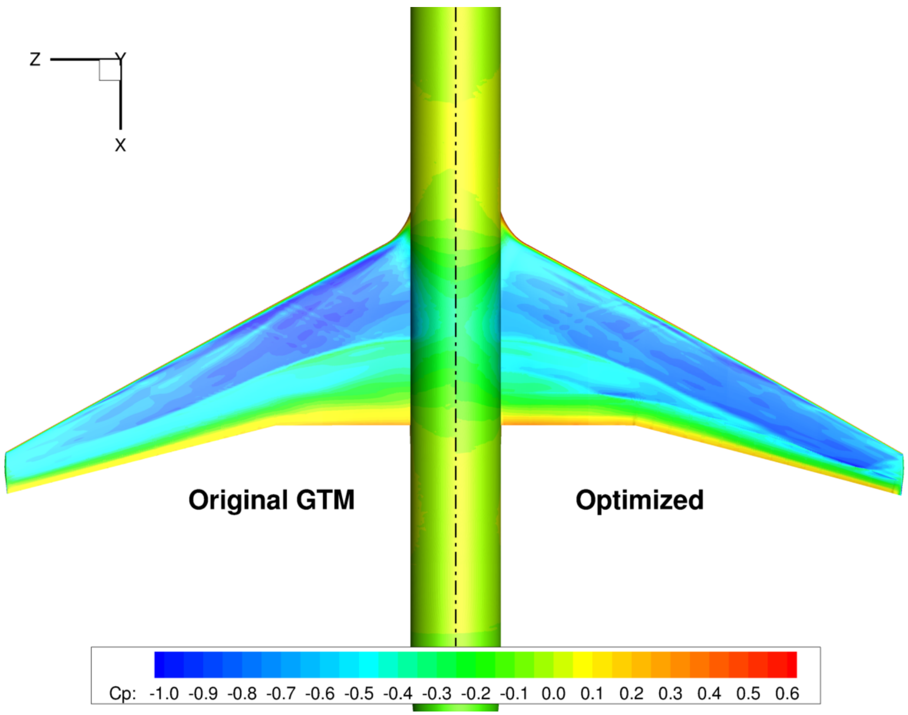
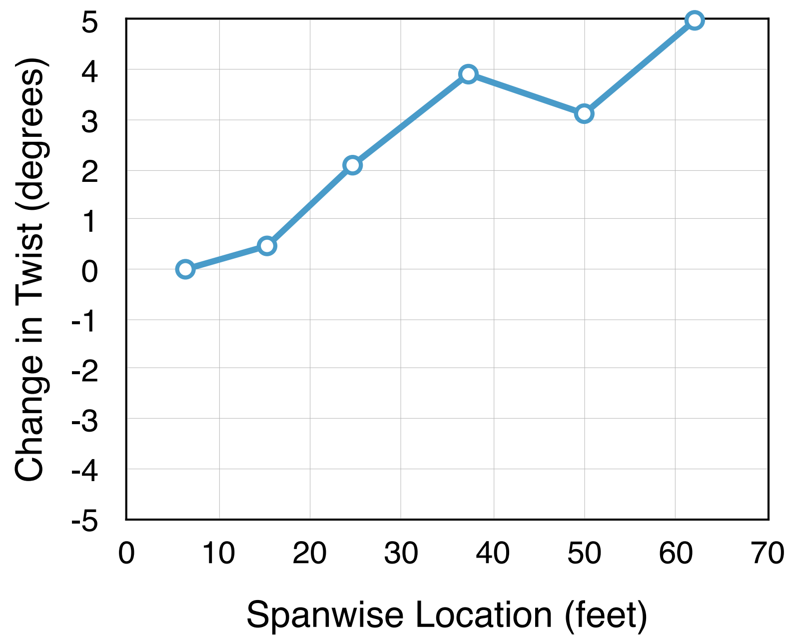
- Optimize flaps (fixed twist)
- Optimize twist and flaps

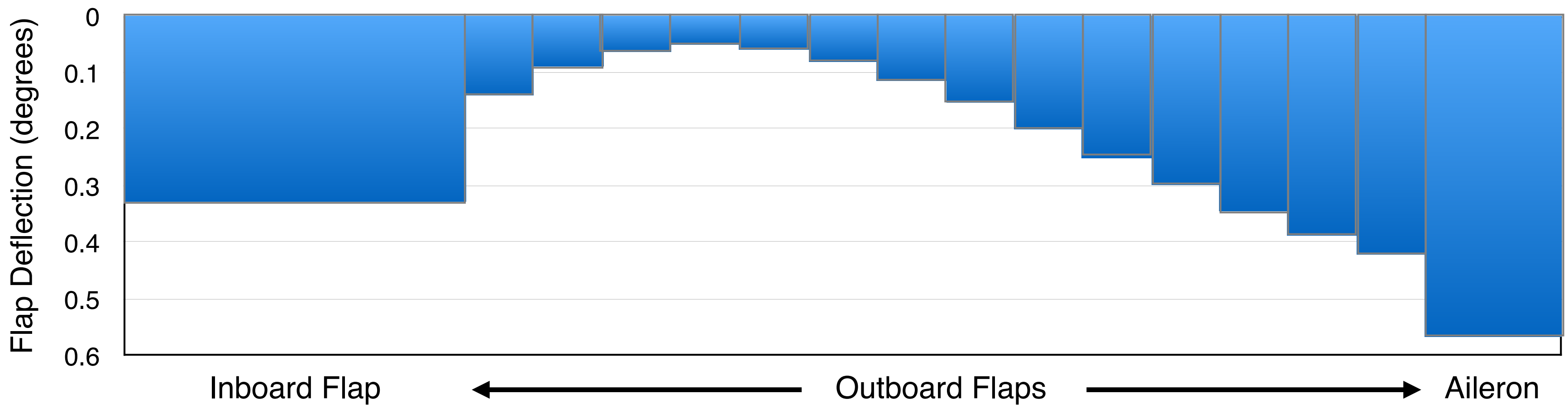




Soft Wing GTM - Mid-Cruise Optimized







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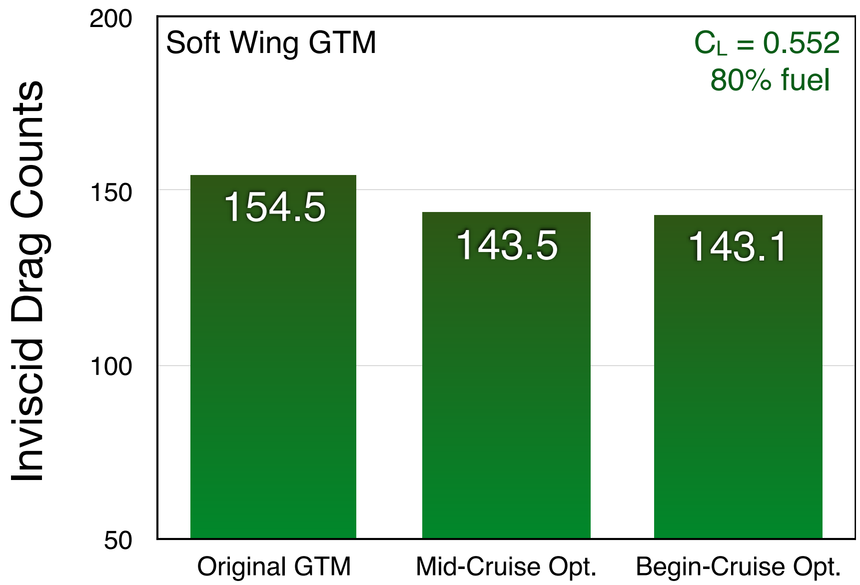
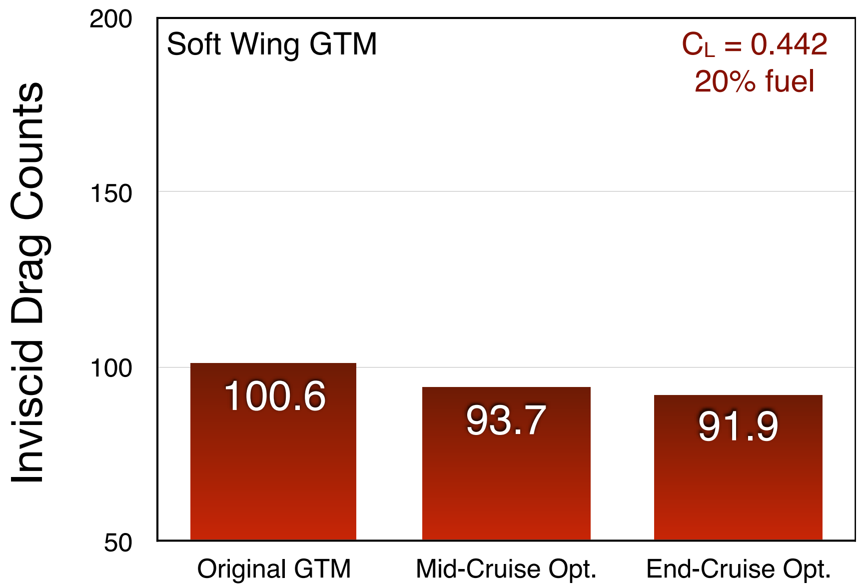
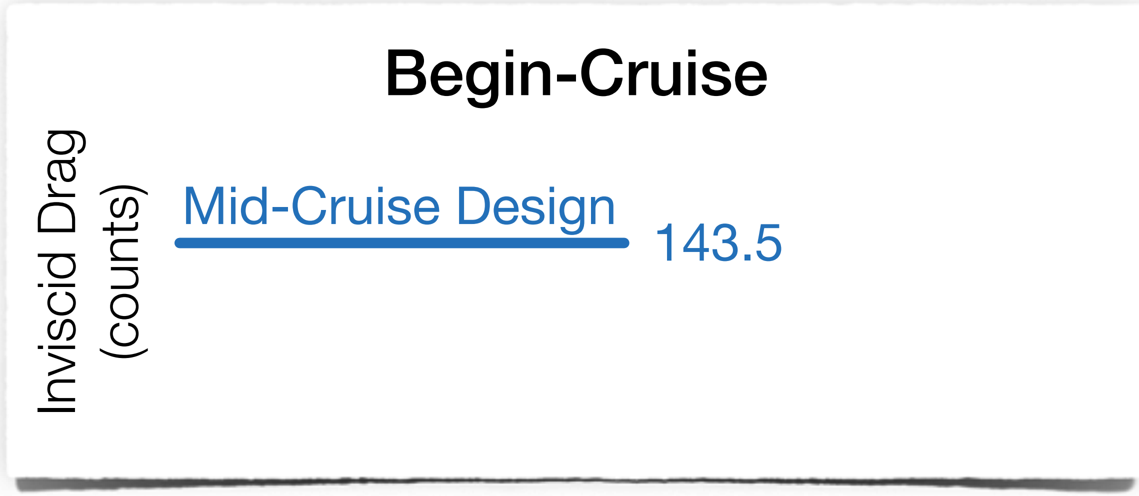
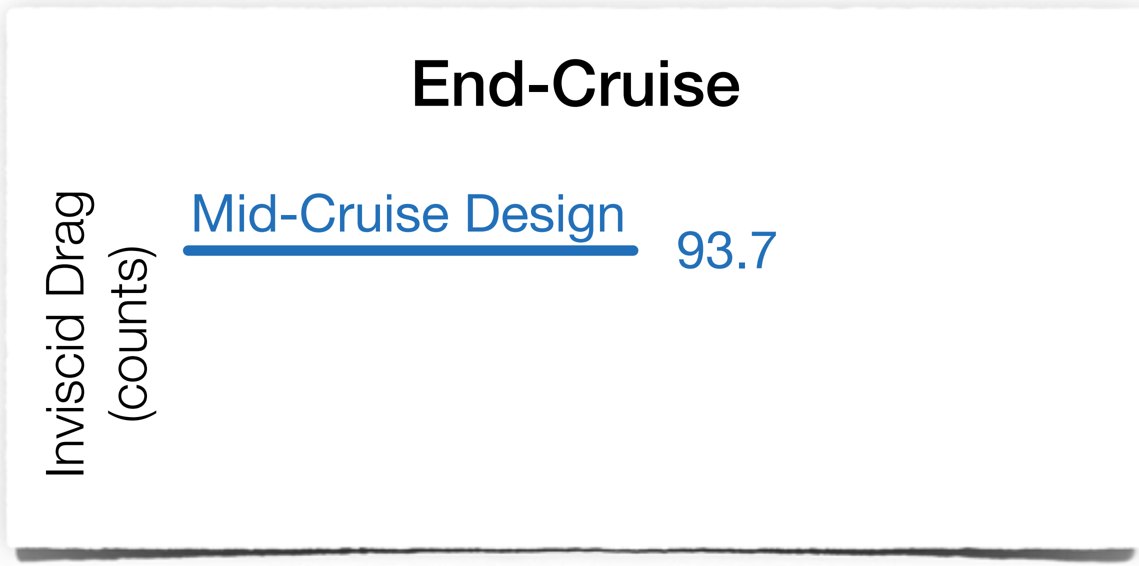




Soft GTM Wing - VCCTEF Adaptation

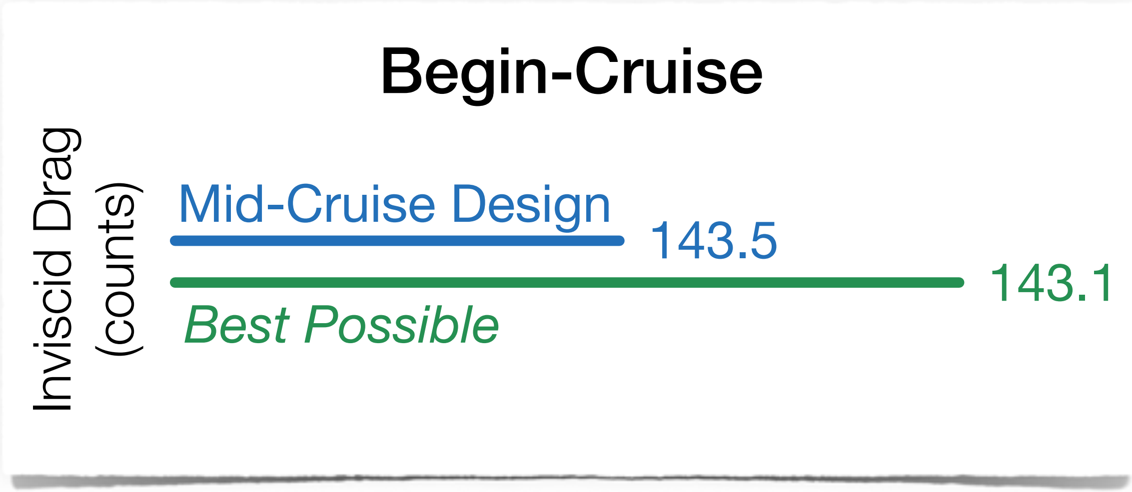
- Start with wing designed for mid-cruise

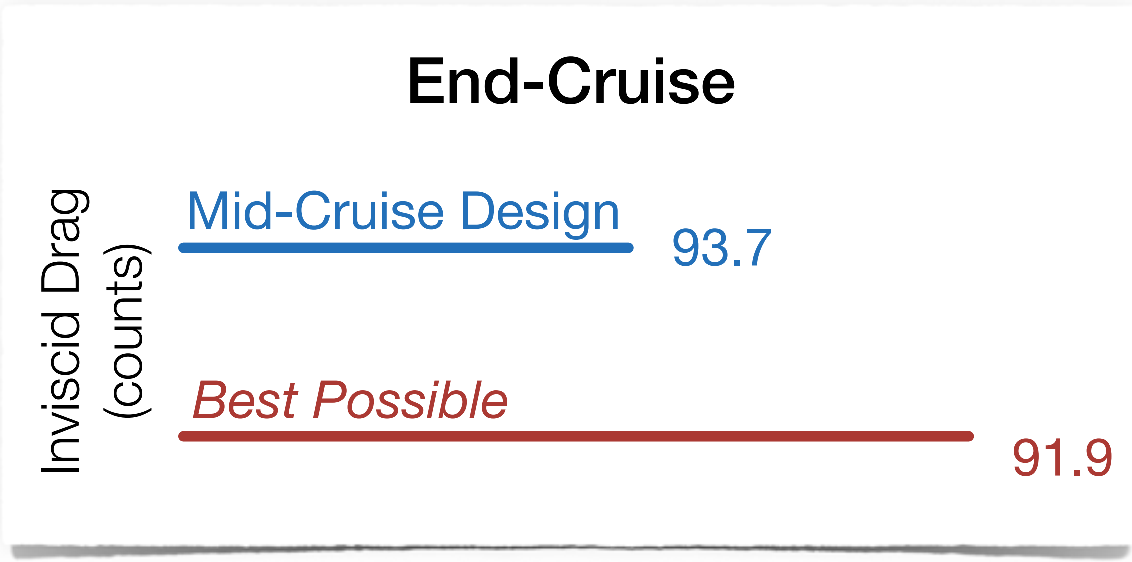




Soft GTM Wing - VCCTEF Adaptation

- Start with wing designed for mid-cruise
- Compare with wing optimized for off-design condition





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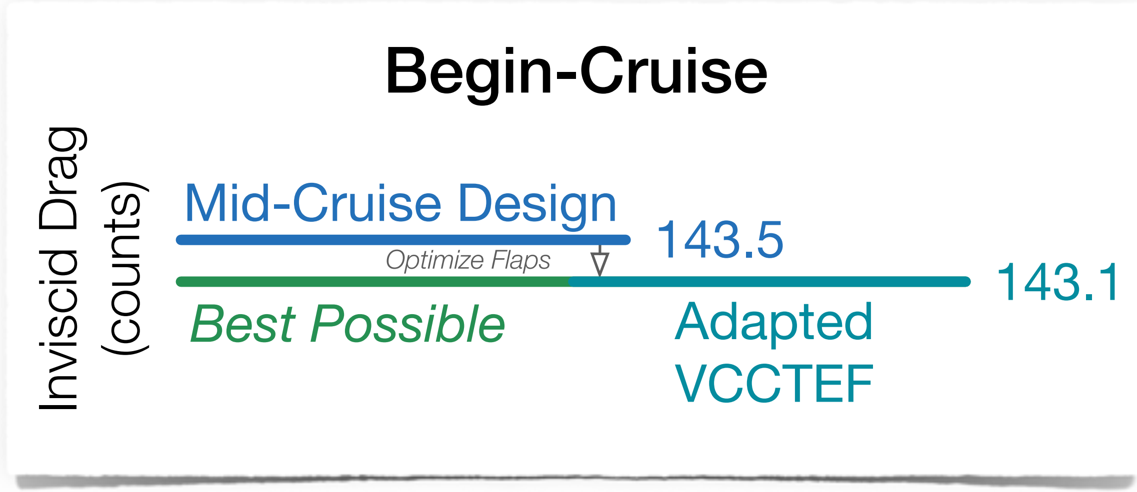

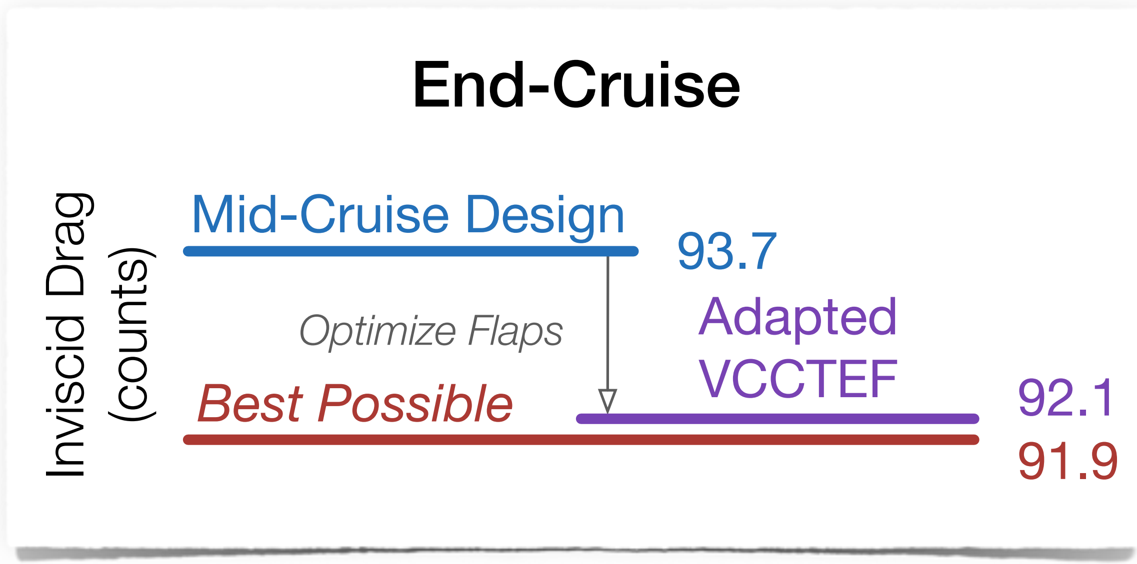

Conclusions

- Fast iterative method developed to aerodynamically optimize transport wings while addressing aeroelastic effects
- VCCTEF system was evaluated on GTM wing (stiff and soft) as a means to improve off-design cruise performance
  - achieved near optimal performance
  - results suggest wave drag could be actively reduced
  - flap system could reshape a wing with constant airfoil section (ease of manufacturing) to a more optimal design for any given flight condition
- Results similar on conventional (stiff) and highly flexible (soft) wings
- Designer of an aircraft with VCCTEF could assume near-optimal performance throughout cruise

Future Work

- Another off-design case - over-speed
  - another common off-design case is flying faster (to keep a schedule)
  - can the VCCTEF improve cruise performance at a higher Mach number?
  - repeat evaluation at Mach 0.827 at mid-cruise
- Evaluate VCCTEF on other transport aircraft designs
  - Truss-Braced Wing
  - Common Research Model (higher aspect ratio)